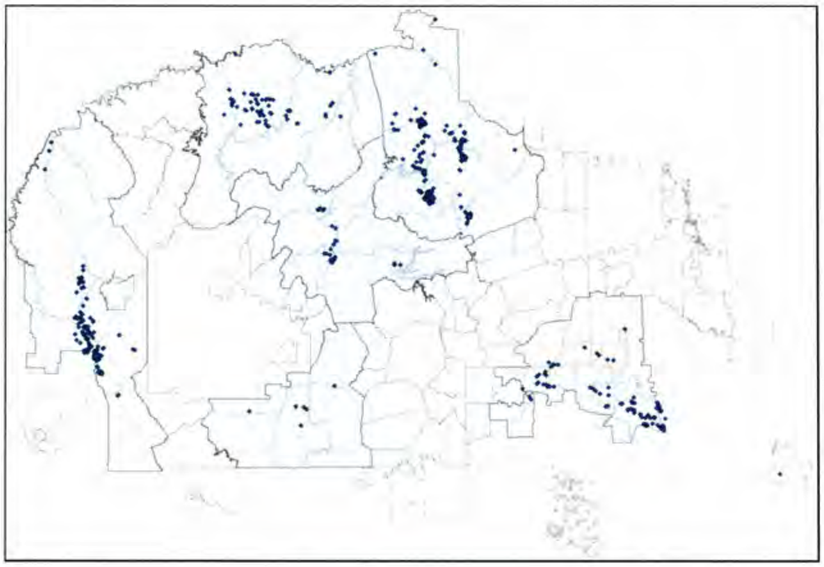
Initial White Paper on Cleanup Options
for Navajo Abandoned Uranium Mines



Prepared pursuant to a contract C010103 with the Navajo Nation
With Participation from:

Navajo Nation Environmental Protection Agency, Superfund Program
Navajo Nation Department of Justice (Navajo DOJ)
United States Environmental Protection Agency (USEPA)

(Input from the Navajo Uranium Commission to be included once the Uranium Commission is appointed)

September 29, 2015

Prepared by:

ROUX ASSOCIATES, INC.

12 Gill Street
Suite 4700
Woburn, MA 01801

Neil M. Ram
Ph.D., LSP, CHMM
Executive Vice President

Larry McTiernan
PG, LSP
Principal Hydrogeologist

Catie Moore
Project Geologist

TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

TABLES

FLOW CHARTS

APPENDICES

EXECUTIVE SUMMARY: INITIAL WHITE PAPER ON CLEANUP OPTIONS FOR NAVAJO ABANDONED URANIUM MINES

This Initial White Paper on Cleanup Options for Navajo Abandoned Uranium Mines (the "Initial White Paper") summarizes the extent and status of surficial contamination arising from past uranium mining within the Navajo Nation and examines the options for addressing the risk that this contamination poses to the people of the Navajo Nation.[1] The White Paper was prepared pursuant to a contract with the Navajo Nation, with participation from multiple stakeholders including the Navajo Nation Environmental Protection Agency (NNEPA), the Navajo Nation Department of Justice, and the U.S. Environmental Protection Agency (USEPA).[2] The Initial White Paper is intended to assist the Navajo Uranium Remediation Advisory Commission and the Navajo people with evaluating options for cleanup of abandoned uranium mines (AUM)[3] waste. The information presented herein has been assembled from discussions with multiple USEPA project managers, knowledgeable environmental professionals, and Navajo stakeholders who are familiar with assessment and cleanup of abandoned uranium mines conducted to date within the Navajo Nation. Findings presented herein are guided both by technical considerations and traditional Navajo governance and planning, including concepts embodied in Diné Fundamental Law. The Initial White Paper has not yet received input from the Navajo Uranium Commission because, as of the date of this report (September 30, 2015), the Uranium Commission has not yet been appointed and the contract under which this Initial White Paper prepared expires on that date. The authors of this Initial White Paper are prepared to continue work to provide more details on the advantages and disadvantages of each of the available options and to incorporate comments from the Uranium Commission and other stakeholders, assuming that additional funding to do so becomes available in the future. Future work would evaluate the advantages and disadvantages of the various cleanup options and associated analysis of alternatives as part of a dynamic interchange, including in-person meetings with the Uranium Commission and the Navajo people.

Overview of AUMs within the Navajo Nation

From approximately the 1940s into the 1980s, uranium mining was conducted throughout the Navajo Nation from mesa tops, rims, canyon walls, and from underground workings. The

---

1 The Initial White Paper focuses only on the risk posed by surficial contamination (i.e., soil contamination and AUM waste piles). It does not include detailed discussion of uranium-impacted structures, groundwater, or surface water. It also does not evaluate non-radiological chemicals of potential concern including arsenic, nickel, thorium, vanadium, nitrate, and sulfate), nor does it provide a point-by-point comparison of remedial alternatives pursuant to CERCLA or Navajo Fundamental Law . It does, however, provide an overview of the general goals of Navajo Fundamental Law and CERCLA requirements in light of future cleanup actions at AUMs.

2 In addition, Roux consulted with two former Navajo Supreme Court Justices, Justices Robert Yazzie and Tom Tso on the nature of Navajo Fundamental Law. While the authors of this White Paper received valuable input from the Justices it is important to note that time constraints prohibited the Justices from conducting a thorough review of all White Paper sections. We believe the discussions relating to Navajo Fundamental Law accurately reflect the input we received. But, in some cases the choice of words in English to express Fundamental Law principles was ours and we take responsibility for any in-artful or inaccurate descriptions contained in this document.

3 In this Initial White Paper, the term "AUMs" refers to both mine sites and transfer stations. Throughout this document, AUM statistics are presented based upon mine claims consistent with the Five-Year Plans. Mine claims consist of one or more mine sites which together share a single production record. The term "cleanup" is used in its broadest sense and does not imply a decision to use a remedial as opposed to a removal approach under CERCLA.

mining waste, which included low-grade uranium ore that was not economical to process, was often placed in waste piles, spilled or dumped down the sides of mesas, or scattered about other portions of the mines. At many AUMs, mining activities resulted in greater potential exposure of the Navajo people (Diné) to radiation when naturally occurring radiological materials ("NORM") became more exposed, more erodible and more permeable (and as a result of this became "technological enhanced" NORM, also known as "TENORM"). Subsequent transport of the waste through wind and water erosion has spread the waste beyond the boundaries of many AUMs. Direct exposure of the Navajo to the mining waste, most of which contains elevated levels of radiological components, may occur as a result of everyday home and work activities, recreational activities (camping, hunting), as well as traditional Navajo cultural activities (herb-gathering, sheep-grazing, and performing ceremonies). Indirect exposure may result where mining waste has been used for road or building construction or where it has been incorporated into building materials. There are also physical hazards associated with open mine pits and adits. In addition to the direct human health impacts and physical hazards, the reminders of past uranium mining and its adverse effects negatively impact the Navajo people's enjoyment of land within the Navajo Nation.

According to the USEPA,[4] there are 523 abandoned uranium mine claims[5] located on the Navajo Nation, as well as numerous homes and drinking-water sources with elevated levels of uranium and its decay products. Large-scale cleanup actions have been performed at five AUMs on the Navajo Nation, including the Skyline Mine (consolidation of AUM waste into a fully encapsulated repository near the AUM), the Cove Transfer Stations and Section 32 Mine (consolidation and stabilization with tackifier),[6] and the NECR and Quivira Mines (consolidation within a stockpile covered with a temporary soil cap).[7] In addition, cleanup has been conducted at the Highway 160 Site, located four miles northeast of Tuba City, AZ.[8] Note that, the term "repository" as used herein means an engineered disposal cell which includes both a liner and an engineered cap that is built in an off-site location or in an on-site area not significantly impacted by AUM waste. A disposal cell built atop a previously existing tailings pile or AUM waste pile is not considered a repository because it does not include a liner. Note also that as used herein, a disposal cell is different from a repository in that it does not include a liner.

---

4 E-Mail from Linda Reeves, USEPA Region 9 to David Taylor, Navajo Nation Department of Justice dated August 7, 2015.

5 Mine claims may consist of multiple AUMs that share one production record. Each mine claim has one production record for all mine sites within a mine claim. For example, the Frank No. 1 mine claim (one mine claim) has three AUMs that share production records under that one mine claim.

6 "Tackifier" and "soil stabilizer" are terms that are often used interchangeably referring to materials that are an eco-safe, biodegradable, liquid copolymer used to stabilize and solidify soil for erosion control and dust suppression.

7 Smaller-scale cleanup actions have been performed at several additional AUMs in the Navajo Nation.

8 January 2013 Five-Year Plan Summary Report. http://www.epa.gov/region6/6sf/newmexico/united_nuclear/navajouraniumreport2013.pdf

The magnitude of the uranium mining legacy on the Navajo Nation is reflected by the following statistics for the 523 mine claims discussed within this Initial White Paper:

1. 409 mine claims have gamma radiation levels more than twice the background level ("above two-times background"), 266 of which have gamma radiation levels above ten-times background;

2. 58 mine claims are located within 1,320 feet of a livestock or human drinking water well;

3. 198 mine claims are located within 200 feet of a structure;

4. 518 AUMs are located within 1 mile of a perennial or intermittent surface water source;[9]

5. 17 mine claims have an occupied residential structure within 200 feet; and

6. 38 mine claims have gamma radiation levels above two-times background and a residential structure located within ¼ mile.

USEPA and NNEPA have identified 46 mine claims as having the highest priority for additional assessment work and cleanup actions, with the criteria for inclusion on this list being: (1) radiation levels at or above ten-times background and where the location of the mine is within ¼ mile of a potentially inhabited house or structure, (2) radiation levels above two-times background and below ten-times background with a potentially inhabited home within 200 feet, and (3) mines with a potential aquatic impact.

Uranium Contamination and Navajo Fundamental Law

Cleanup of radiologically impacted mining waste within the Navajo Nation is typically undertaken not only in a manner consistent with federal and Navajo regulations but also in a manner that is consistent with inherent beliefs of the Navajo. Decisions on how to address uranium impacts are based on critical thinking and evaluation of the problem from different angles, including consideration of impacts to local populations. Decisions about remedy selection are to be open and transparent to all stakeholders, with no hard feelings (Nayleeh) to provide a harmonious relationship (Hoozho) throughout the decision-making process. Notwithstanding the Navajo Nation's stated desire to remove uranium-impacted material from Navajo land, under some circumstances the use of engineered containment cells to manage AUM waste on Navajo land could be seen as being within the framework of Navajo Fundamental Law, which is based on experience rather than a set of rules. However, where containment cells are used on Navajo Nation land and thus limit the Navajos' ability to use and enjoy their land (essentially taking the land from the Navajo), compensatory measures including providing additional land to the Navajo Nation may need to be considered.

[9] Tables 4 through 9 of the 2007 Atlas indicate a total surface water score of 160 for every AUM evaluated.

On April 24, 2015, the 23rd Navajo Nation Council formerly resolved[10] to establish the Diné Uranium Remediation Advisory Commission as "*an advisory commission in the Executive Branch of the Navajo Nation Government*" with the goal to develop "*measureable objectives and devising practical and publically acceptable plans for remediation*[11] *and restoration*[12] *of the lands to protect current and future generations from uranium mining and process wastes, in accordance with the Fundamental Laws of the Diné*."

Uranium Contamination on the Navajo Nation, Assessment Techniques and Data Needs

Assessment of surficial radiological impacts can be conducted using aerial radiological surveys or GPS-based gamma surveys. Radioactivity at depth can be assessed using conventional drilling rigs along with smaller GeoProbe sampling equipment. Other methods can be used to determine radiological impacts of groundwater, water supplies, and surface water. Radioactivity can also be assessed for contaminated structures, as well as air and dust. Much progress has been made in understanding the nature and extent of radiological and other impacts at AUMs.

Information has been gathered from Weston Solutions (Weston) site screen reports, the 2007 Atlas[13], and other Weston spreadsheets about the volume of AUM waste, the magnitude of radiological impacts, the number and status of adits, and the proximity of AUMs to residential structures. Although this information characterizes the impacts at AUMs, data needs remain, including but not limited to additional information regarding (a) the duration and frequency of Navajo people's exposure to AUM contamination, (b) the quality of unregulated water sources, (c) radon from open adits, (d) areas of AUMs without radiological data because of steep grades, and (e) potential migration of uranium impacted dust from AUMs.

Cleanup of Uranium Contamination Conducted To Date Within or Near the Navajo Nation

Large-scale cleanup performed to date at AUMs and other uranium-related sites within the Navajo Nation has been limited to (1) Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) cleanup actions at five AUMs,[14] (2) Uranium Mill Tailings Restoration Control Act (UMTRCA)[15] cleanup actions at five former uranium mills, and (3) one Navajo Nation/US Department of Energy (USDOE) cleanup action at a

---

10 CAP-14-15. Resolution of the Navajo Nation Council. 23rd Navajo Nation Council, First year, 2015, an action relating to law and order, resources and development and naabik'iyati' committees and Navajo Nation Council; amending 2 N.N.C.§3580 to create a Diné uranium remediation advisory commission.

11 "Remediation" is defined by the Uranium Commission Master Plan as, "the permanent closure of uranium mining and uranium processing sites, waste piles and associated buildings for the purposes of eliminating or substantially reducing releases of radioactive and toxic substances to the air, land and water in such ways as to prevent or substantially minimize human exposure to such substances now and for future generations. 18 N.N.C.§1302.D.

12 "Restoration" is defined by the Uranium Commission Master Plan as, "returning land, vegetation, water and air to its original state, or as close to its original state as is technologically possible, without regard to cost, in accordance with the duty of the Diné to protect and preserve the beauty of the natural world for future generations, as set forth in 1 N.N.C.§205.G.

13 Abandoned Uranium Mines and The Navajo Nation, Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data August, 2007.

14 Smaller-scale cleanup actions have been performed at several additional AUMs in the Navajo Nation.

15 Uranium Mill Tailings Restoration Control Act of 1978.

mill-related site.[16] Therefore, to augment the amount of information available for use in this Initial White Paper, documentation was reviewed for one AUM (the San Mateo Mine, located in the nearby Grants Mining District) and ten uranium-related sites[17] in the vicinity of the Navajo Nation at which cleanup has been performed under CERCLA or UMTRCA. This review is summarized in **Table 1**. A number of lessons can be learned from these remedial actions; these lessons fall into three broad categories discussed below.

<u>Problems With Revegetation</u>

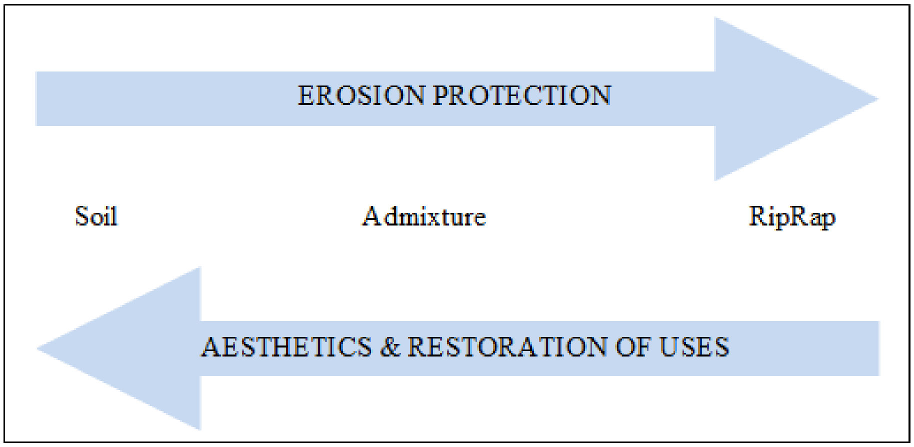
Not surprisingly given the arid climate of the Navajo Nation, vegetation of constructed caps and revegetation of areas disturbed by remedial action has been difficult at several sites, including the Skyline Mine, San Mateo Mine, and Cove Transfer Station 1. Experience at other sites demonstrates, however, that given time, caps and disturbed areas can be successfully vegetated. But constructed caps cannot be allowed to simply vegetate on their own; frequent and sometime extensive maintenance and repair is often needed.

<u>Long-Term Integrity of Disposal Cells:</u>

The long-term integrity of disposal cells, where used to contain waste at or near a site, is of paramount importance to the long-term protectiveness of the remedy. While caps composed of soil with vegetative cover most closely represent pre-mining terrain, they require the most maintenance to ensure long-term protectiveness, given their greater susceptibility to erosion. Admixture and riprap afford progressively greater protection from erosion but at the same time are progressively more obtrusive and limiting with respect to future use of the site. This tradeoff between aesthetics and erosion is depicted in the figure which follows.

[16] Cleanup actions within the Navajo Nation include: **NECR and Quivira Church Rock #1 Mines:** Consolidation of AUM waste within a stockpile covered with a temporary soil cap; **Skyline Mine**: Consolidation of AUM waste into a fully encapsulated repository at the AUM; **Cove Transfer Stations** and **Section 32 Mine:** Consolidation of AUM waste and stabilization of stockpile with tackifier; **UMTRCA (Shiprock, Tuba City, Monument Valley, Mexican Hat and Church Rock):** Consolidation of uranium mill tailings in capped disposal cells at the former mill sites; and **Highway 160:** Contaminated materials excavated and transported outside the Navajo Nation for final disposal.

[17] Cleanup actions outside the Navajo Nation include: **San Mateo Mine**: Consolidation of AUM waste on-site in a capped disposal cell; **Superfund Sites (Homestake, Uravan, Monticello):** Consolidation of uranium mill tailings in capped (and lined in one case) disposal cells at or near the former mill sites; and **UMTRCA (Ambrosia Lake, Slick Rock, Durango, Naturita, Gunnison, Bluewater, and L-Bar):** Consolidation of uranium mill tailings in capped disposal cells at the former mill sites.



Considerations for Armoring

Riprap may also allow greater infiltration compared to soil/vegetative cover and thus require incorporating additional components (e.g., HDPE liner) into the cap design, which may increase costs. However, if a soil cap is preferred in lieu of more armored caps for aesthetics or restoration of uses reasons (e.g., grazing and other Navajo traditional practices), sufficient funds may need to be budgeted for maintenance and repair of the cap in perpetuity (more so than for an armored cap). It may be less expensive in the long run to build a less expensive soil cap with allowance made for periodic maintenance and repair; a detailed cost analysis (which is beyond the scope of this White Paper) would be needed to determine if this is, in fact, the case.

Cost

The various cleanup actions performed to date at AUMs in and near the Navajo Nation have cost between roughly $1 million and $10 million per site. The cost range reflects a number of variables, including the volume of contaminated material excavated, the method of disposal, the disposal location, and logistical factors, with higher cost associated with either disposal outside the Navajo Nation (as in the case of Tuba City Highway 160 site) or lining and capping a repository with HDPE geomembranes (as in the case of Skyline Mine). For future cleanups, the added value of disposal outside the Navajo Nation and/or construction of a lined repository may need to be weighed against the cost involved with respect to the total available funds to address all or some subset of the AUMs on the Navajo Nation.

Options for the Cleanup of AUMs on the Navajo Nation

Containment is the only type of general cleanup action suitable for addressing AUM waste. Under the general category of containment, there are only two process options available:

- Containment of the waste at the AUM (with or without excavation); or
- Containment of the waste elsewhere (either on or off the Navajo Nation).[18]

[18] As discussed in Section 3 of this White Paper, notwithstanding the Navajo Nation's desire to remove uranium-impacted material from Navajo land, under some circumstances the use of engineered containment cells or repositories to manage AUM waste on Navajo land may be within the framework of Navajo Fundamental Law, which is based on experience rather than a set of rules.

Containment of AUM waste at the AUM (with or without excavation) is the most direct and cost-effective approach assuming site conditions, public sentiment, and engineering logistics permit such an approach.[19] Available remedial alternatives under this process option include capping the waste without excavation, consolidating the waste into a smaller area (i.e., atop existing waste), or excavating the waste for consolidation in a new repository at the AUM. Where site conditions, engineering logistics, and/or public sentiment do not favor containing the AUM waste at the AUM, then radiological-impacted materials can be excavated and contained elsewhere, either within or outside the Navajo Nation. For containment within the Navajo Nation, four cleanup alternatives are available: (a) containment near the AUM (e.g. at a nearby AUM or other acceptable nearby location), (b) containment in a local repository, (c) containment in a regional repository or (d) containment in a single, centralized repository. Remedial alternative selection typically considers criteria set forth in the National Contingency Plan as well as those provided in the Navajo Nation CERCLA (Title 4, Navajo Nation Code, Chapter 17) including but not limited to the following evaluation criteria set forth in §2305 (Response action selection), at paragraph H (Requirements for Remedial Actions):

- The long-term uncertainties associated with land disposal;
- The goals, objectives, and requirements of the Navajo Nation Solid Waste Code;
- The persistence, toxicity, mobility, and propensity to bioaccumulate of such hazardous substances, pollutants, or contaminants and their constituents;
- Short- and long-term potential for adverse health effects from human exposure;
- Long-term maintenance costs;
- The potential for future remedial action costs if the alternative remedial action in question were to fail; and
- The potential threat to human health and the environment associated with excavation, transportation, and re-disposal, or containment.

For example, the potential short-term risk and disruption of transporting AUM waste from individual AUMs need to be weighed against the long-term effectiveness of consolidating AUM wastes in regional repositories or in a centralized repository where periodic maintenance could be achieved more cost-effectively than by containment at or near individual AUMs.

NNEPA has expressed strong support for a policy that favors removal of all uranium waste from the Navajo Nation. As stated by former NNEPA Executive Director, Stephen B. Etsitty, "*This policy has arisen from the Navajo Nation's long experience with the legacy of uranium mining within the Navajo Nation. The policy is designed to reduce the impact of uranium mining waste on significant customs and cultural values that are unique to the Navajo people. The policy is also the result of the risks to human health and the*

[19] This statement assumes that funding for perpetual maintenance is available, as would be required for both containment at the AUM and containment elsewhere (if on the Navajo Nation).

environment from uranium mine waste." In addition, while it is not within the scope of this Initial White Paper to develop a full analysis of the advantages and disadvantages of the option, including removal of all uranium waste from the Navajo Nation, it is important to note that considerations at the various AUMs may vary. Differences that could be important include waste volume, accessibility, topography, degree of radioactivity, proximity of water bodies and residences, proximity of underlying uranium ore bodies to the surface and other factors. As stated earlier, future work could include in-person meetings to discuss the options with the Uranium Commission and the Navajo people.

There are five major factors to consider in selecting containment cleanup alternatives for an AUM:

(a) **Location:** Decision-makers need to consider whether or not to contain the AUM waste at the AUM or to excavate and dispose of it elsewhere (either on or off the Navajo Nation). Containment at the AUM may be favored where the AUM is readily accessible for periodic inspection and monitoring, local roads are adequate for repeated heavy vehicle access (e.g., for ongoing maintenance), the terrain supports cap construction and maintenance, and where NORM or TENORM would be exposed if the AUM waste were to be removed. Conversely, the engineering controls needed to safely contain waste at the AUM are more challenging where residents live, where surface water features exist near the AUM, where groundwater near the AUM is used for livestock or human drinking water and/or where local climatological conditions (e.g., freeze/thaw cycles, higher precipitation) may increase the cost for cap construction and containment relative to the cost to transport the waste elsewhere. In such cases, AUM waste excavation and disposal elsewhere may be the preferred alternative.

(b) **Full or partial encapsulation:** If the waste is to be excavated and contained at the AUM, a determination is typically needed as to whether or not the disposal cell in which the waste is to be contained should be lined. While the disposal cell must always include a surface cover as a radiation shield, decision-makers must also evaluate the need for a liner to provide further groundwater protection (i.e., beyond that provided by the cover). In addition, full encapsulation of the waste may address cultural perspectives, for example by fully containing the Yellow Monster (*Leetso).*

(c) **Armoring and drainage**: The cover design for a disposal cell or repository must attempt to strike a balance between protection (i.e., ensuring the long-term integrity of the cover), aesthetics, and future land use. Knowing that storm water can result in channelization and erosion, covers may be designed with an understanding of potential future channel erosion so that the cover which remains after such erosion is still sufficiently protective. This may require significant armoring, which could in turn detract from aesthetics and/or limit future use (see next item).

(d) **Future Use:** Decision-makers need to consider whether and to what extent cleanup alternatives that entail containment of AUM waste within the Navajo Nation might limit future use of an AUM site or other Navajo land (in the case of an off-site repository). Most alternatives involving containment within the Navajo Nation may require certain restrictions on future use (e.g., precluding residential use and use of groundwater); however, most may allow for many other uses, including most traditional Navajo uses (herb gathering etc.), provided that adequate radiation shielding (as determined, for example, by the PRG calculator[20] or other suitable risk assessment approach) is provided and maintained in perpetuity.

(e) **Future inspection and maintenance to ensure long-term integrity**: The long-term integrity of AUM waste disposal cells and repositories are of paramount importance to the long-term protectiveness of the selected remedy. Soil and admixture covers need to be periodically inspected and repaired if erosion and/or other damage are evident. In order for soil and admixture covers to be sustainable, they may need to be periodically inspected and maintained. While vegetation typically improves the aesthetics and the potential for restoration of traditional uses of the land on which a cap is constructed, establishing native vegetation at sites is difficult because of normal climatic variability and potential die-off during drought. Frequent and sometimes extensive maintenance and repair may be needed. This needs to be considered and addressed as part of a long-term inspection and maintenance program.

These and other factors are discussed within this Initial White Paper along with a decision framework to help select the cleanup alternative which best applies to a particular AUM. This decision framework results in six viable alternatives for AUM cleanup:

Alternative 1: Cap the AUM waste in-place at the AUM, without any excavation or consolidation;

Alternative 2: Excavate/consolidate the AUM waste and contain it at the AUM (within a smaller footprint);

Alternative 3: Excavate/consolidate the AUM waste and contain it in a new repository located at the AUM;

Alternative 4: Excavate/consolidate the AUM waste and contain it at a nearby AUM;

Alternative 5: Excavate/consolidate the AUM waste and contain it in a local, regional or central repository located within the Navajo Nation; or

Alternative 6: Excavate the AUM waste and dispose of it outside the Navajo Nation.

To further streamline the cleanup selection process for a particular AUM, **Table 2** that follows lists the minimum requirements (AUM characteristics and other considerations) for each of the six alternatives identified above (including the three sub-options for Alternative 5). These minimum requirements must be met for an alternative to be considered truly viable for a particular AUM. For example, AUM waste at an AUM may need to be limited to one or more discrete piles in order for Alternative 1 (capping in-place at the AUM) to be considered a viable alternative for that AUM. Looked at another way, these requirements are limiting factors, i.e., factors which, if *not* met for a particular AUM, may *preclude* the

[20] The Preliminary Remediation Goals (PRGs) for Radionuclides electronic calculator, known as the Rad PRG calculator is described at http://epa-prgs.ornl.gov/radionuclides/ and discussed in USEPA's June 14, 2014 memorandum on "Radiation Risk Assessment at CERCLA Sites: Q&A" at http://nepis.epa.gov/Exe/ZyPDF.cgi/P100K3TC.PDF?Dockey=P100K3TC.PDF

selection of one or more alternatives for that AUM. For example, if residents live near a particular AUM, alternatives entailing on-site consolidation of AUM waste (Alternatives 1, 2, and 3) may not be appropriate for that AUM. Note that Alternative 6 (excavation with disposal outside the Navajo Nation) has no limiting factors; consequently, this alternative will be viable for all AUMs.

Table 2: Screeneing Criteria for AUM Waste Clean-up Alternatives

AUM Characteristics and Other Considerations*	Remedial Alternatives							
	Alternative 1: Cap the AUM waste in-place at the AUM	Alternative 2: Excavate and consolidate the AUM waste and contain it at the AUM	Alternative 3: Excavate and consolidate the AUM waste and contain it in a new repository	Alternative 4: Excavate and consolidate the AUM waste and contain it at a nearby AUM	Alternative 5: Excavate and consolidate the AUM waste and contain it in a:			Alternative 6: Excavate the AUM waste and dispose of it outside the Navajo Nation
					Local Repository	Regional Repository	Central Repository	
No residents within 1/4 mile of AUM	✓	✓	✓					
No surface water within 1/4 mile of AUM	✓	✓	✓					
Groundwater within 1 mile of AUM not used for drinking water and/or livestock watering	✓	✓	✓					
Relatively easy to access (for periodic inspections/monitoring)	✓	✓	✓					
Roads adequate for repeated heavy vehicle access (for ongoing maintenance as needed)	✓	✓	✓					
Terrain supports cap constructability	✓	✓	✓					
Climatological conditions (freeze/thaw cycles, higher precipitation) won't increase cost for cap construction beyond cost to transport waste elsewhere	✓	✓	✓					No limiting factors
Liner not desired/warranted	✓	✓						
Waste limited to discrete pile(s)	✓							
Adequate space at AUM for repository (limited excavation required to build)			✓					
AUM amenable to on-site containment located nearby				✓				
Suitable location for repository nearby					✓			
Suitable location for repository within AUM region						✓		
Suitable centralized location for repository available within Navajo Nation							✓	

* The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

Use of the above table can allow decision-makers to screen the various alternatives listed above before moving forward with a more detailed analysis of alternatives for a particular AUM taking into account variables such as short-term risk and cost. As can be seen, some alternatives may have more minimum requirements than others; as a result, these alternatives can likely be screened out more often than those with fewer requirements. Alternative 6, which has no limiting factors, will typically not be screened out.

Following the above alternative selection, various design decisions need to be considered to complete the cleanup. This includes different cap designs (HDPE membranes, ET caps, capillary barriers, frost protection layers, riprap/gravel veneer covers, soil or admixture covers) that are typically considered for all of the alternatives that include containing the AUM waste at a location within the Navajo Nation. Further, where a liner is desired or warranted, there are two primary liner designs (single-lined or doubled-lined) that may be considered. In addition, a variety of possible materials may be considered for lining the containment area. In selecting the cap design, future use of the land upon which the cap is constructed also needs to be considered, ranging from limited restrictions (e.g., only prohibiting residential use) to more stringent restrictions (e.g., precluding most traditional Navajo uses).

Perhaps the most important design consideration is whether or not to armor the cap. The type of material used in cap construction is dependent upon containment/repository features (top slope, edge slope) and site features (contributing watershed, historical flooding, etc.) as well as the desired future use of the cap. Cap design also needs to consider whether it can be vegetated and whether such vegetation can survive episodic droughts. The cap design often considers stormwater flow channelization and associated erosion that may occur over time. Finally, cap design will need to consider the degree to which traditional Navajo uses of the surface may be restored, such as grazing sheep and growing plants that are important within the Navajo culture. The nature of the cap and the maintenance demands will depend, among other factors, on the extent to which there is an effort to engineer the cap with an eye to restoring some of the Navajo's traditional uses of the surface, while protecting people and the environment from contact with the waste.

The ultimate selection of a cleanup alternative to address AUM waste at each individual AUM may therefore be dependent upon the evaluation criteria set forth in CERCLA, the NCP and the Navajo Nation CERCLA considering multi-faceted and AUM-specific technical and cost considerations in light of the goals to minimize risk and maximize AUM restoration for future Navajo traditional use including but not limited to grazing, hunting, herb gathering and ceremonial purposes.

1.0 INTRODUCTION

This Initial White Paper on Cleanup Options for Navajo Abandoned Uranium Mines (the "Initial White Paper") summarizes the current status of known contamination arising from past uranium mining and processing within the Navajo Nation and examines the options for addressing the elevated risks that this waste continues to pose to the people of the Navajo Nation. This Initial White Paper:

(a) Provides options for cleanup of abandoned uranium mine (AUM)[21] waste consistent with Diné Fundamental Law, the Diné Natural Resources Protection Act of 2005, CERCLA, and the Radioactive Materials Transportation Act.[22] There are two overarching cleanup options: (a) consolidation into capped on-site repositories[23] and (b) excavation with off-site disposal. Cleanup options for selecting on-site vs. off-site consolidation consider various site parameters such as terrain, accessibility, remoteness, surface grade, rock volume, proximity to populations and others. The off-site disposal option considers facilities both on and off the Navajo Nation.

(b) Provides an overview of the current status of AUM waste within the Navajo Nation, including a discussion of the human health risks associated with uranium exposure, and the current status of abandoned uranium mines on the Navajo Nation.

(c) Provides a discussion of Navajo Fundamental Law, Diné Uranium Remediation Advisory Commission and Navajo Nation's Department of Justice position regarding institutional controls and cleanup of uranium mines.

---

21 In this Initial White Paper, the term "AUMs" refers to both mine sites and transfer stations. Throughout this document, AUM statistics are presented based upon mine claims consistent with the Five-Year Plans. Mine claims consist of one or more mine sites which together share a single production record. The term "cleanup" is used in its broadest sense and does not imply a decision to use a remedial as opposed to a removal approach under CERCLA.

22 The Initial White Paper focuses only on the risk posed by surficial contamination (i.e., soil contamination and waste rock piles). It does not include detailed discussion of uranium-impacted structures, groundwater, or surface water. It also does not evaluate non-radiological chemicals of potential concern including arsenic, nickel, thorium, vanadium, nitrate, and sulfate), nor does it provide a point-by-point comparison of remedial alternatives pursuant to CERCLA or Navajo Fundamental Law. It does, however, provide an overview of the general goals of Navajo Fundamental Law and CERCLA requirements in light of future remedial actions at AUMs.

23 The term "repository" as used herein means an engineered disposal cell which includes both a liner and an engineered cap that is built in an off-site location or in an on-site area not significantly impacted by AUM waste. A disposal cell built atop a previously existing tailings pile or AUM waste pile is not considered a repository because it does not include a liner. Note also that as used herein, a disposal cell is different from a repository in that it does not include a liner.

(d) Describes the assessment techniques used to delineate and quantify impacts of such contamination as well as data quality considerations and data needs.

(e) Summarizes cleanup actions taken to-date to address AUM waste and the lessons learned from such actions.

(f) Reviews the applicable and appropriate technologies to permanently dispose or isolate AUM wastes with particular attention to the armoring, drainage, and long-term integrity of capping and encapsulating technology.

The Initial White Paper was prepared pursuant to a contract with the Navajo Nation, with participation from multiple stakeholders including the Navajo Nation Environmental Protection Agency, Superfund Program, the Navajo Nation Department of Justice and the United States Environmental Protection Agency.[24] The information presented herein has been assembled from discussions with multiple project managers, other knowledgeable environmental professionals, and Navajo stakeholders who are familiar with uranium assessment and cleanup conducted within the Navajo Nation as of June 2015. Recommendations presented herein are guided both by technical considerations and traditional Navajo governance and planning, including concepts embodied in Diné Fundamental Law.

The Initial White Paper has not yet received input from the Navajo Uranium Commission because, as of the date of this report (September 30, 2015), the Uranium Commission has not yet been appointed and the contract under which this Initial White Paper prepared expires on that date. The authors of this Initial White Paper are prepared to continue work to provide more details on the advantages and disadvantages of each of the available options and to incorporate comments from the Uranium Commission and other stakeholders, assuming that additional funding to do so becomes available in the future. Future work would evaluate the advantages and disadvantages of the various cleanup options and associated analysis of alternatives as part of a dynamic interchange, including in-person meetings with the Uranium Commission and the Navajo people.

[24] In addition, Roux consulted with two former Navajo Supreme Court Justices, Justices Robert Yazzie and Tom Tsoe on the nature of Navajo Fundamental Law; however, due to time constraints the Justices have not reviewed this Initial White Paper, so additions or revisions to the description of Fundamental Law may be appropriate in future iterations of this report.

2.0 OVERVIEW OF AUMS WITHIN THE NAVAJO NATION

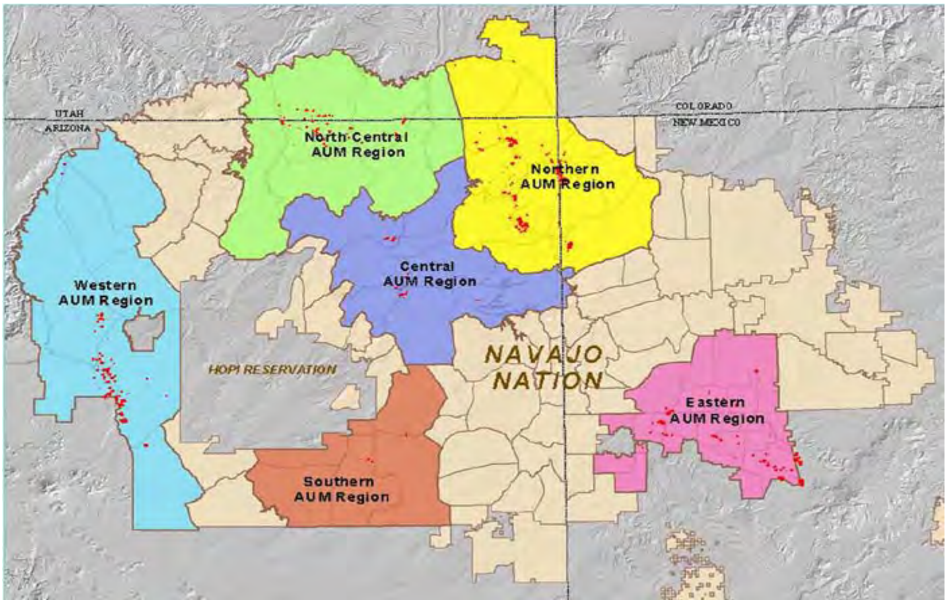
The lands of the Navajo Nation include 27,000 square miles over three states in the Four Corners area.[25] Their unique geology makes them rich in uranium, a radioactive ore in high demand after the development of atomic weapons at the close of World War II. From 1944 to 1986, nearly four million tons of uranium ore was extracted from Navajo lands under various leases with the Navajo Nation. During this time, particularly in the 1940s, private mining companies conducted exploration and production of uranium ore which they sold to the U.S. Government for its nuclear energy program. By 1967, the USAEC had ample reserves of uranium and in 1970, the USAEC discontinued the purchase of uranium from commercial mining companies. Although uranium was needed for private sector power plants, the demand for US uranium significantly diminished in the 1970s. Based on rising concerns about uranium mining contamination, the Navajo Nation banned new uranium mining and or processing within its borders in the Diné Fundamental Law, the Diné Natural Resources Protection Act of 2005.

Uranium mining was conducted throughout the Navajo Nation, as depicted in the figure which follows showing locations of AUMs, defined in this report as "*uranium mines that have been deserted and are no longer being maintained*." From the approximately the 1940s into the 1980s, uranium ore was mined primarily from mesa tops, rims, and from canyon walls (i.e., surface mining) and from underground workings.[26]

---

[25] USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, "Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation," 2014.

[26] 2007 Atlas, Part II: Atlas with Geospatial Data, page 1-13 (Figure 6. Mine Production for the Lukachukai Mountains).



Navajo Nation AUM Regions - AUM sites shown in red[27]

Mining operations included removing uranium ore by hand from the mine pits and/or mine shafts and loading materials into small carts. The waste rock, which included low-grade uranium ore, was either left in waste piles or dumped down the sides of the mesas[28] or left along other portions of what are now AUMs. At many AUMs, mining activities resulted in greater potential exposure of the Navajo people (Diné) to radiation when naturally occurring radiological materials ("NORM") became more exposed, more erodible and more permeable (and as a result of this became "technological enhanced" NORM, also known as "TENORM").

2.1 Human Health Risks Associated with AUMs

Uranium mine waste generally contains lower levels of uranium than the ore that was extracted and taken for milling; however, these wastes can contain levels of uranium and its breakdown products that pose a substantial risk to human health. Specifically Radium 226, a "daughter" product of uranium, is found at most AUMs. According to USEPA, "*[h]ealth effects as a result of exposure to these elements can include lung cancer, bone cancer, and impaired kidney function.*"[29]

As explained in greater detail below, direct exposure to radioactive waste piles as well as to radioactive media that have been transported from the waste rock piles may occur on the

27 USEPA Region 9 Website; www.epa.gov/region09.
28 Personal communication, Bill Stevens, Former Tronox Project Manager, November 6, 2009.
29 http://www.epa.gov/region9/superfund/navajo-nation/pdf/NavajoUraniumReport2013.pdf

Navajo Nation during cultural activities (hunting, herb gathering, sheep grazing, and performing ceremonies) and recreational activities (camping, hiking etc.). Exposure pathways include:

(a) Direct radiation exposure proximate to the waste rock piles;

(b) Direct radiation exposure to radioactive materials used in building structures;

(c) Ingestion of radiologically-impacted groundwater used for drinking water supply;

(d) Ingestion of and dermal contact with radiologically-impacted surface waters;

(e) Ingestion of animals or plants that have been exposed and contaminated with uranium;

(f) Inhalation and/or ingestion of windblown radioactive dust;[30] and

(g) Inhalation of radon gas emitted from mine ventilation shafts.

In addition, while reclamation by the Navajo Nation Abandoned Mine Lands (AML) program has reduced most of the more obvious threats, there is still the potential for physical injuries associated with open portals, adits,[31] vertical openings, inclines and declines, pits, rim cuts, high walls, and embankments.

The frequency of potential exposure to AUMs is dictated by use of the contaminated areas by sheep-grazers, hikers, campers, herb-gatherers, medicine men, ceremonial users, horse-back riders, and individuals using all-terrain vehicles. Human exposure pathways include direct exposure to radiologically-impacted material(s) on or adjacent to waste rock piles etc. and/or inhalation or accidental ingestion of contaminated soil and/or dust disturbed by recreational/cultural activities. Nearly 13% of participants in a survey conducted by the Diné Network for Environmental Health (DiNEH) indicated that they played on mine waste.[32] An example of such exposures is provided by Larry King, a member of the Navajo Nation who stated that "*as a kid, I played on the big piles of ore and mine waste across the road from our*

[30] 2007 Atlas Part I: Navajo Nation AUM Screening Assessment Report.
[31] An adit is a mine opening.
[32] Uranium Legacy Impacts on Health in Eastern Navajo Agency. Diné Network for Environmental Health, Project Update. September 15, 2010.

home, unaware of the dangers."[33] Similarly, Edith Hood, another member of the Navajo Nation, stated "*children still play in the fields and ditches among the rocky mesas and the arroyo that once carried contaminated mine water*."[34]

Exposures to radiologically-impacted material also occur during hunting and grazing. Mr. Perry Charley testified at deposition taken in connection with the Tronox Bankruptcy trial that the land where mines are located is used for ranching, sheepherding, and summer camps. He explained: "*During the summer, to protect the sheep and the cattle from heat, excessive amount of heat in this desert environment, the Navajos move up to their summer camps. And they live there approximately five to six months out of the year*." He further explained that because of the number of abandoned uranium mines, the livestock have no choice but to graze among those areas.[35] Mr. Charley also explained that some shepherds even use AUMs as pens for their livestock or shelter for themselves.[36] Human exposure to radiologically-impacted game also is discussed in a 2006 Northern AUM Region Screening Assessment Report, which states that "*it is advisable that livestock not graze on areas where AUMs are located.*"[37] According to Edith Hood, "*the sheep still get through the fence that is supposed to barricade these uranium mine tailings, and yet we still eat the sheep for mutton*."[38] Ms. Hood added, "*we have lambs that did not have wool, hair, but they died within days. And we have butchered sheep and in one case the fat was yellow, which is not normal*."[39] Mr. Charley testified that it is important from a tribal perspective that all parts of sheep, goats and cattle are consumed.[40] Over 13% of the participants in the DiNEH survey reported herding livestock on contaminated land.[41]

---

33 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

34 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

35 Perry Charley deposition, May 17, 2011, p. 26-27.

36 Perry Charley deposition, May 17, 2011, p. 45.

37 2006 Northern AUM Region Screening Assessment Report.

38 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

39 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

40 Perry Charley Deposition, May 17, 2011, p. 44.

41 Uranium Legacy Impacts on Health in Eastern Navajo Agency. Diné Network for Environmental Health (DinéH) Project Update. September 15, 2010.

Livestock and game are exposed to radiologically-impacted material via foraging on vegetation where radionuclides have been directly deposited or taken up by the root system, resulting in radiologically impacted milk, meat, or eggs.[42] The radionuclide concentration in an animal product is dependent upon the ingested amount of radiologically-impacted forage and/or water.[43] As discussed in a 1986 publication by the Southwest Research and Information Center, animals that drank regularly from the radiologically-impacted river water had higher-than-normal levels of radioactive elements in their bodies.[44] Further, radionuclides bioaccumulate in fish,[45] thereby providing yet another exposure pathway to both humans and foraging animals.

Human exposure to radiologically-impacted material also occurs via swimming in radiologically-impacted surface water (ingestion and dermal contact) and by the cultural practice of the Navajo people to gather herbs and/or native plants on or near AUMs. As described by deLemos et al., these plants are often used by Navajos in traditional medicines and ceremonies.[46] Mr. Charley confirmed that plants from contaminated areas are used by Navajos for medicinal properties, as herbs or in their prayers or ceremonies.[47] Mr. Charley testified that Navajos would even use uranium-contaminated materials, which were yellow, as body paints, for sand painting, and for prayers and ceremonial activities because they did not understand that it was radioactive.[48] Mr. Charley also testified that children play in ponds in areas where contaminated materials were dumped.[49]

---

42 National Council on Radiation Protection and Measurements. Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment. April 1984.

43 National Council on Radiation Protection and Measurements. Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment. April 1984.

44 The Workbook. The Puerco River: Where did the water go?. Southwest Research and Information Center. Vol. XI, No. 1. Jan./Mar., 1986.

45 National Council on Radiation Protection and Measurements. Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment. April 1984.

46 DeLemos et al., Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. Environmental Health, July 2009.

47 Perry Charley deposition, May 17, 2011, p. 44.

48 Perry Charley deposition, May 17, 2011, p. 60.

49 Perry Charley deposition, May 17, 2011, p, 46.

The use of uranium-mine waste materials for building construction has been well documented by the USEPA[50] and was confirmed by Stephen Etsitty of NNEPA,[51] Representative Dennis Kucinich, and Representative Henry Waxman who stated that, "*Mill tailings and chunks of uranium ore were used to build foundations, floors and walls for some Navajo homes.*"[52] In fact, 17.1% of participants in the DiNEH study reported using mine materials in their homes.[53] Radioactive materials from waste piles left near roads or rural communities were historically transported and used in the construction of homes, schools, or other buildings, resulting in elevated levels of radiation to building inhabitants. In addition, as explained by deLemos et al.,[54] contaminated sediment has also been used to repair roads that have washed out. Dermal exposure and incidental ingestion of such contaminated sediment may occur during repair activities.

Windblown dust from AUMs can also settle on food crops, resulting in direct ingestion of metals and radionuclides in dust from the mining areas. Further, because of the relatively dry climate and lack of infrastructure in these relatively remote locations, Navajo ranchers collect stormwater runoff (that has the potential to be radiologically impacted) as drinking water for their livestock.[55] There is also the potential for residents to ingest the meat and/or milk from cattle or mutton that graze on contaminated land and/or drink contaminated water.[56]

DeLemos et al. indicate that over 50% of residents studied drink from unregulated water sources, and over 80% of Navajo families haul drinking water from wells intended for

---

50 U.S. Environmental Protection Agency, Technical Report on Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining, August 2007.

51 The Navajo Nation Environmental Protection Agency was established in 1995 with the charge of protecting human health, welfare and the environment of the Navajo Nation (Navajo Nation Environmental Protection Agency Website (www.navajonationepa.org).

52 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

53 Uranium Legacy Impacts on Health in Eastern Navajo Agency. Diné Network for Environmental Health Project Update. September 15, 2010.

54 DeLemos et al., Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. Environmental Health, July 2009.

55 Office of Surface Mining Reclamation and Enforcement, 1999. *Annual Evaluation Report for the Abandoned Mine Land Reclamation Program Administered by the Navajo Nation.*

56 National Council on Radiation Protection and Measurements. Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment. April 1984.

livestock use only.[57] Water hauling is widespread on the Navajo Nation; according to the Five-Year Plan to Address Uranium Contamination on Navajo Nation, up to 30% of households are not connected to a public water supply system, and may haul water from livestock wells, community wells, and natural springs which may not be approved for human consumption.[58] Mr. Charley confirmed that in areas where public water supply is not available, Navajo people use these unregulated water sources for domestic purposes.[59] As described by Phil Harrison, a member of the Navajo Nation, "*if the water source runs out, then you would go to the mines to collect water for drinking water*."[60] According to the Diné Policy Institute, "*ingestion of contaminated water has been identified as the exposure pathway of greatest concern.*"[61] As described in the March 2006 Northern AUM Region Screening Assessment Report, several sites came to USEPA's attention because of elevated radionuclide activity in water samples.

Radon (^{222}Rn) is also emitted from uranium mine ventilations shaft exhaust and is therefore another major source of environmental contamination within the Navajo Nation. According to Xie, et. al.,[62] "*due to their alpha-emitting short lived progeny* ^{218}Po, ^{214}Po, *and* ^{222}Rn *are recognized as main causative agents for lung cancer when presented in high radon inhalation such as ….those encountered in uranium mining area*." The researchers determined that wind profiles, surface roughness and topographic conditions were significant in the radon dispersion process.

These exposure routes are corroborated by a survey conducted by the DiNEH study, which conducted a community based study of over 1,300 residents of the Navajo Nation.[63] The study evaluated the association between exposure to mines and/or mine wastes and a number of health conditions, including high blood pressure and diabetes. The DiNEH study

57 DeLemos et al., Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. Environmental Health, July 2009.

58 Five-Year Plan to Address Uranium Contamination on Navajo Nation: Navajo Uranium Stakeholder Workshop. November 2009.

59 Perry Charley deposition, May 17, 2011, p. 44.

60 The Health and Environmental Impacts of Uranium Contamination in the Navajo Nation. Hearing before the Committee on Oversight and Government Reform. House of Representatives. One Hundred Tenth Congress. First Session. October 23, 2007.

61 Diné Policy Institute. Uranium and Diné Binitsekees: An analysis of the direct and in-direct consequences of uranium using Navajo principles.

62 Dong Xie, H. Wang, K. Kearfott, Z Liu and S. Mo, "Radon dispersion modeling and dose assessment for uranium mine ventilation shaft exhausts under neutral atmospheric stability," Journal of Environmental Radioactivity, 129 (2014) 67-62.

63 Uranium Legacy Impacts on Health in Eastern Navajo Agency. Diné Network for Environmental Health Project Update. September 15, 2010.

concluded that "*People living in areas with greatest number of mine features can have twice the risk of hypertension when all other significant factors - kidney disease, diabetes, family history of disease, BMI, age and gender - are accounted for as the baseline.*"[64]

There are also numerous physical hazards associated with the AUMs. Perry Charley is a member of the Navajo Nation who has spent his entire adult life working on issues related to the impact of uranium mining on the Navajo Nation. Among other things, Mr. Charley prepared an inventory of the scope of mining activities on Navajo Nation and the hazards posed from mining to the Navajo public and environment as part of the Navajo Nation Abandoned Mined Lands Reclamation Program (AML).[65] Mr. Charley testified at deposition that physical hazards from AUMs included human exposure to open adits and vertical openings and the risk of mines collapsing with someone inside them.[66] Some of these hazards were addressed pursuant to grants to AML from the United States Office of Surface Mining, Reclamation & Enforcement's Surface Mine Control and Reclamation Act program, during the period 1994 to 2015, which expended approximately $3.5M[67]on various mine reclamation activities at AUMs.[68]

In addition to the direct human health impacts and physical hazards, AUM waste adversely impacts the Navajo people's use of land within the Navajo Nation. The Navajo use the land for ranching, sheepherding, hunting and for ceremonial purposes.[69] The land in the mountains is used by the Navajo for camps during the summer months in order to protect their sheep and cattle from the excessive heat of the desert environment.[70] The land is also the natural habitat for various wildlife including endangered species.[71] In addition,

64 Uranium Legacy Impacts on Health in Eastern Navajo Agency. Diné Network for Environmental Health Project Update. September 15, 2010.

65 Perry Charley deposition, May 17, 2011, p. 15. 47.

66 Perry Charley deposition, May 17, 2011, p. 42.

67 Office of Surface Mining Reclamation and Enforcement Annual Evaluation Report Evaluation Year 2004 (July 1, 2003 through June 30, 2004) on the Navajo Nation Abandoned Mined Lands Reclamation Program website: http://www.aml.navajo-nsn.gov/News_Rprts/AML/OSM_AER_Nav2004.pdf.

68 The United States Department of the Interior Budget Justifications and Performance Information Fiscal Year 2015 Office of Surface mining and Enforcement website: http://www.osmre.gov/resources/budget/docs/FY2015_Justification.pdf

69 Deposition of Perry Charley, May 17, 2011, p. 26.

70 Deposition of Perry Charley, May 17, 2011, p. 26.

71 Deposition of Perry Charley, May 17, 2011, p. 26.

vegetation on the land such as herbs, are used medicinally, in tribal ceremonies and prayers, and by livestock for grazing.[72]

2.2 Current Status of AUMs

The Navajo AML Reclamation Program, established in 1988,[73] has successfully reclaimed all the inventoried coal sites as well as 913 uranium mine features and 33 copper mines. The abandoned mines include both surface mines such as open pit, rimstrips, trenches, and underground mines with features like portals/adits, incline and vertical shafts.[74] In addition several uranium mines have been addressed in efforts to achieve federal CERCLA standards:

- **Skyline Mine**: Consolidation of AUM waste into a fully encapsulated repository at the AUM;
- **The Cove Transfer Stations and Section 32 Mine:** Consolidation and stabilization with tackifier; and
- **The NECR and Quivira Mines:** Consolidation within a stockpile covered with a temporary soil cap.

Additionally, cleanup under the Uranium Mill Tailings Radiation Control Act of 1978 were performed by USDOE or the former operator at five uranium mills sites (where uranium ore was processed) located within the Navajo Nation.[75] In addition, cleanup has been conducted at the Highway 160 Site located four miles northeast of Tuba City, AZ.[76] The Highway 160 site is the only example of where all of the contaminated materials were excavated and taken to a location outside the Navajo Nation (the USDOE-operated Cheney Cell in Grand Junction, Colorado) for final disposal.

Tens of millions of tons of radioactive and chemically hazardous uranium wastes still exist in uncontrolled piles within the boundaries of the four Navajo Sacred Mountains (the San

---

72 Deposition of Perry Charley, May 17, 2011, p. 44.

73 Vernon Maldonado, "Office of Surface Mining Reclamation and Enforcement Annual Evaluation Report, Evaluation Year 2005, Navajo Nation Abandoned Mined Lands Reclamation Program." http://www.aml.navajo-nsn.gov/News_Rprts/AML/OSM_AER_Nav2005.pdf

74 http://www.aml.navajo-nsn.gov/AML_Files/AMLReclamationPage.html

75 Shiprock, Tuba City, Monument Valley, Mexican Hat and Church Rock.

76 January 2013 Five-Year Plan Summary Report. http://www.epa.gov/region6/6sf/newmexico/united_nuclear/navajouraniumreport2013.pdf

Francisco Peaks near Flagstaff, Arizona; Mt. Taylor near Grants, New Mexico; Hesperus Peak in southwestern Colorado; and Mt. Blanco in southeastern Colorado). Many of these uranium waste sites are located within a short distance of Navajo homes. According to USEPA,[77] there are 523 abandoned uranium mine claims located on or near the Navajo Nation. Of these, USEPA and NNEPA have identified 46 as having the highest priority for additional assessment work and cleanup actions (see table that follows).

46 Priority Abandoned Uranium Mine Claims - Navajo Nation

12/24/2014

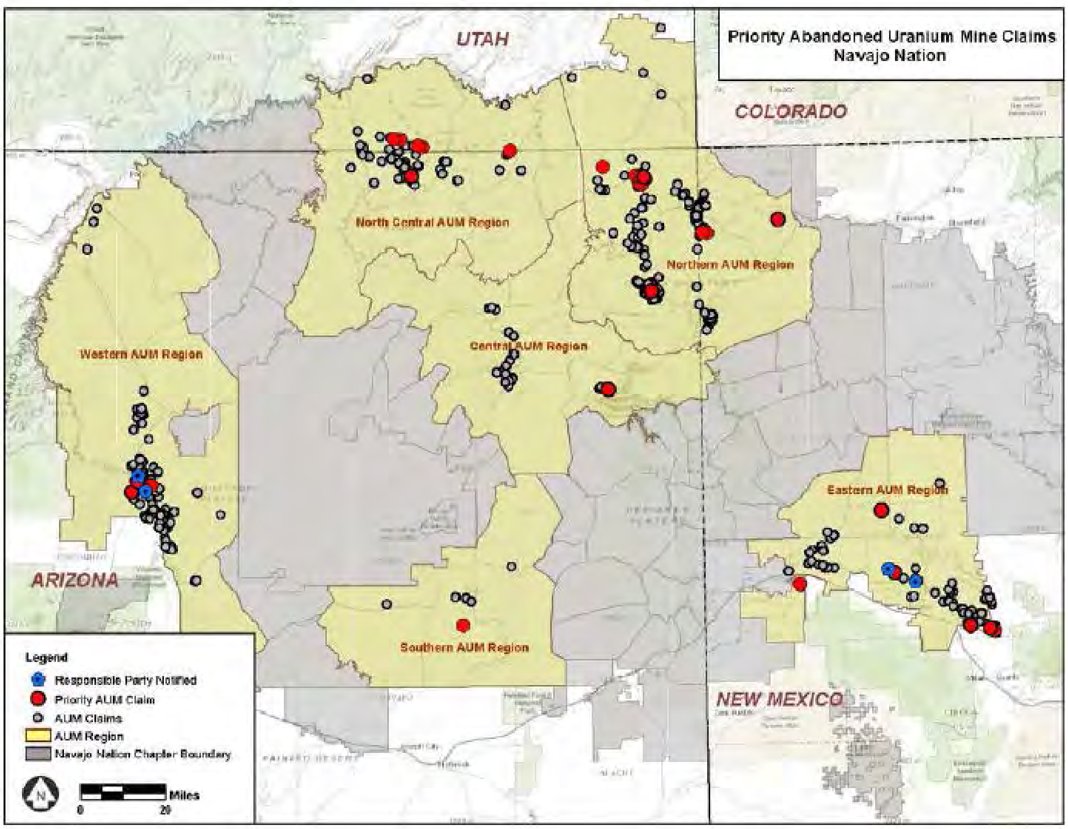
Mine Site IDs	Mine Claim Name	Chapter	Notes
2	Alongo Mines	Red Valley	> 10 times background and occupied structure within 1/4 mile
78	Claim 28	Black Mesa	> 9 times background, occupied structure within 1/4 mile, potential aquatic resources im
457, 458, 459	Section 9 Lease	State of Arizona	> 10 times background and potential aquatic resources impact
1006	Standing Rock	Nahodishgish	> 2 times background and occupied structure within 200 feet
1011, 1012, 1035	Section 26	Baca / Haystack	> 2 times background and occupied structure within 200 feet
1033	Section 24 (Nanabah Vandever)	Baca / Haystack	> 10 times background and occupied structure within 1/4 mile
119	Charles Huskon No. 12	Coalmine Mesa	> 10 times background and occupied structure within 1/4 mile
135	Boyd Tisi No. 2	Coalmine Mesa	> 10 times background and occupied structure within 1/4 mile
136	Juan Horse No. 3	Coalmine Mesa	> 10 times background and occupied structure within 1/4 mile
175	A & B No. 2	Cameron	> 10 times background and occupied structure within 1/4 mile
220	Barton 3	Red Mesa	> 10 times background and occupied structure within 1/4 mile
223	Rock Door No. 1	Oljato	> 10 times background and occupied structure within 1/4 mile
225	Charles Keith	Oljato	> 10 times background and occupied structure within 1/4 mile
228	A & B No. 3	Cameron	> 10 times background and occupied structure within 1/4 mile
239	Harvey Blackwater No. 3	Kayenta	> 10 times background and occupied structure within 1/4 mile
254	Skyline	Oljato	> 10 times background and occupied structure within 1/4 mile
260	Mitten No. 3	Oljato	> 10 times background and occupied structure within 1/4 mile
296	Occurrence B	Chinle	> 2 times background and occupied structure within 200 feet
301, 317	Mariano Lake	Mariano Lake	> 10 times background and occupied structure within 1/4 mile
304	NE Church Rock	Pinedale	> 10 times background and occupied structure within 1/4 mile
305	NE Church Rock No. 1	Coyote Canyon	> 2 times background, occupied structure within 1/4 mile, PRP identified
313	Eunice Becenti	Church Rock	> 10 times background and occupied structure within 1/4 mile
318	Mac No. 1	Mariano Lake	> 2 times background and occupied structure within 200 feet
319	Black Jack No. 2	Smith Lake	> 10 times background and occupied structure within 1/4 mile
323	Ruby No. 3	Smith Lake	> 10 times background and occupied structure within 1/4 mile
344	Haystack No. 1	Baca / Haystack	> 10 times background and occupied structure within 1/4 mile
363, 365, 366	Section 25	State of New Mexico	> 10 times background and occupied structure within 1/4 mile
364	Section 23	Baca / Haystack	> 10 times background and occupied structure within 1/4 mile
382	Charles Huskon No. 14	Cameron	> 10 times background and occupied structure within 1/4 mile
424	Mesa III, Northwest Mine	Cove	> 10 times background and occupied structure within 1/4 mile
486	Oak124, Oak125	Red Valley	> 10 times background and occupied structure within 1/4 mile
487	King Tutt Point	Red Valley	> 10 times background and occupied structure within 1/4 mile
513	Firelight No. 6	Oljato	> 10 times background and occupied structure within 1/4 mile
55	Tsosie 1	Sweetwater / Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
57	North Martin	Sweetwater	> 10 times background and occupied structure within 1/4 mile
59	NA-0904	Sweetwater / Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
604	Mesa II 1/2, Mine 4	Cove	> 10 times background and occupied structure within 1/4 mile
605	Mesa III Mine	Cove	> 10 times background and occupied structure within 1/4 mile
63	NA-0928	Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
634	Plot 6	Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
635, 636	Hoskie Henry	Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
664	Plot 3	Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
667	Climax Transfer Station	Shiprock	> 2 times background and occupied structure within 200 feet
71	Black Rock Point Mines	Teec Nos Pos	> 10 times background and occupied structure within 1/4 mile
852	Hoskie Tso No. 1	Indian Wells	> 10 times background and occupied structure within 1/4 mile
93, 94, 654, 655, 656, 657	Mesa I, Mine Nos. 10-15	Cove	> 10 times background and potential aquatic resources impact

46 High Priority AUMs Provided by USEPA

[77] E-Mail from Linda Reeves, USEPA Region 9 to David Taylor, Navajo Nation Department of Justice dated August 7, 2015.

According to the Second Five-Year Report,[78] the most urgent cleanup work will be conducted at mines likely to pose a risk to human health or the environment based on mines that exhibit:

- Gamma radiation more than ten times background levels and are located within a quarter mile of a potentially inhabited structures (38 mine claims);
- Gamma radiation more than two times background and located within 200 feet of a potentially inhabited structure (five mine claims);
- A potential impact to aquatic resources such as streams and wetlands (seven mine claims); and
- Mines targeted for actions from 2014 through 2018 (see figure that follows).



High Priority Abandoned Uranium Mine Sites
(taken from Second Five-Year Plan)[79]

78 USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, “Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation,” 2014.

79 USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, “Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation,” 2014.

In a 2014 report, the U.S. Government Accountability Office (GAO) concluded that:

(a) Additional assessment is needed at 41 of the highest priority abandoned uranium mines ranging from scanning the entire mine sites to identifying contaminant boundaries to more thorough assessments including engineering evaluation/cost analysis (EE/CA) reports to support potential non time critical removal actions or an RI/FS to support cleanup.[80]

(b) Most of the remaining highest priority abandoned mines may need additional cleanup actions.

(c) GAO estimated, based upon costs incurred at the Skyline Mine, it could cost a minimum of $150 million to fund cleanup actions at just half of the highest priority mines (21 mines).

In 2014, the USDOE issued a report to Congress[81] addressing:

(a) The location of defense-related abandoned uranium mines on federal, state, tribal and private lands;

(b) The extent of radiation hazards, other public health and safety threats, and environmental degradation caused, or that may have been caused, by the mines;

(c) A priority ranking to reclaim and cleanup the mines. (Mine reclamation typically involves mitigating the physical hazards by closing shafts and adits and stabilizing and covering the waste rock pile. Cleanup typically addresses contaminated groundwater, removing waste rock piles and other surrounding soils that exceed cleanup levels and placement of the removed material into either an on-site or off-site disposal cell.);

(d) The potential cost and feasibility of reclamation and cleanup in accordance with applicable federal law; and

(e) The status of any mine reclamation and cleanup efforts.

---

80 Note that 31 of the 46 priority mines are now covered by either AOCs or a settlement with the U.S. to conduct assessments.

81 U.S. Department of Energy, Defense Related Uranium Mines, Report to Congress, August 2014, USDOE Washington, DC.

As summarized in the table which follows, the 2014 USDOE report assigned mines into production-size categories ranging from Small (0-100 tons) to Very Large (>500,000 tons) based on the amount of uranium ore sold to the USAEC. Information was gathered from federal and state agency databases, a tribal abandoned mine land program, a private company, and public input. Overall, the USDOE identified 4,225 mines that provided uranium ore to the USAEC between 1947 and 1970. Approximately 11 percent of these mines are on tribal lands.

Tons of Ore Produced	Mine Production-Size Category	Range of Reclamation Costs	Range of Remediation Costs
0–100	Small	$10,000–$70,000	$10,000–$80,000
100–1,000	Small/Medium	$10,000–$80,000	$20,000–$100,000
1,000–10,000	Medium	$50,000–$250,000	$110,000–$840,000
10,000–100,000	Medium/Large	$270,000–$730,000	$2,500,000–$6,500,000
100,000–500,000	Large	$560,000–$1,400,000	$4,900,000–$15,400,000
>500,000	Very Large	Not Estimated	Not Estimated

Reclamation and Remediation Costs Assembled by USDOE

(Note that the two actions are not additive because remediation cost estimates include activities that are also included in reclamation)

The 2014 USDOE report cautioned that the above cost ranges may be underestimated "*if there are challenging, site-specific construction conditions or if repositories cannot be located near groups of mines or if material must be transported to a commercial facility*." This certainly may be the case for abandoned uranium mines located in remote areas such as the Lukachukai Mountains. For example, in a June 24, 2011 Expert Report prepared as part of the Tronox *vs*. Anadarko litigation estimated the cost to cleanup 40 former Kerr-McGee mines located in the Lukachukai Mountains and Tse Tah Region and one uranium transfer station in Cove, NM of the Navajo Nation. Ore production from these mines ranged from minor to 274,000 tons. Waste rock remaining at the mines ranged from minor to 87,000 cubic yards. The estimated cost to cleanup these sites using excavation and off-site disposal of waste rock (in 2005 dollars) was estimated at $198 million which, adjusted to 2015 dollars using inflation factors derived from the GNP Implicit Price Deflators published by the U.S. Department of Commerce, Bureau of Economic Analysis,[82] is $238M[83] (~$5.9M per

[82] https://research.stlouisfed.org/fred2/series/GNPDEF/dowloaddata?cid=21
[83] Q1 2015 GNP of 109.195 divided by Q1 2005 GNP of 90.861 is equal to 1.201.

location). This estimate corresponds to the lower range of the $4.9M to $15.4M cost estimated by USDOE for "large" (100,000 tons to 500,000 tons ore) production mines.

2.3 AUM Database

To better understand the spatial distribution and features of AUMs on the Navajo Nation, a database of mine features was compiled ("AUM Database"), and coupled with geospatial data. Data sources used to compile the AUM Database included:

1. Hardcopies of the Weston Solutions (Weston) Site Screen reports;[84]
2. An Excel file provided by Weston that contained additional information regarding waste pile dimensions, physical characteristics and location;[85]
3. A Weston "AUM Atlas database" Excel file that contained some of the information collected in the Weston Site Screen reports in Excel format; and
4. Hazard ranking system (HRS) scoring for groundwater, soil, air, surface water, and combined scores from the 2007 Atlas (Tables 4 through 9).[86]

Each of the data sources described above provided different information pertinent to understanding the number, size, nature and locations of the AUMs. From 2007 through 2011, Weston conducted site screens of abandoned uranium mines in the Navajo Nation. These Weston site screen reports provided detailed hand-written notes for 521 Weston Site Screen reports that surveyed the 523 mine claims in the Central, Eastern, North Central, Northern Southern and Western regions. The Weston site screen reports contained visual descriptions of mine features that were surveyed on foot (portals, adits, waste piles), reclamation status, a summary of gamma readings collected at each location, and photographs of sites (if they were accessible). Information from the Site Screen reports was combined with the additional Weston spreadsheets described above (the waste pile Excel spreadsheet, and the AUM Atlas database), which provided additional detailed information about the size and features of waste rock at AUM sites. Finally, the HRS scoring developed by USEPA's Region 9 Superfund Site Assessment and Technical Support Team was also linked to each of the

84 Weston conducted "Navajo Abandoned Uranium Mine Site Screen Reports" as part of USEPA's Region IX Navajo AUM Project.

85 Spreadsheet entitled "Weston Waste Pile info" provided to Roux Associates on June 14, 2013.

86 Abandoned Uranium Mines and The Navajo Nation, Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data August, 2007 (Table 4 - Table 9).

AUMs in the database. The HRS scoring system ranked probable Navajo exposure pathways to each of the media evaluated (taking into account proximity of mines to structures, surface water, and drinking water sources). By compiling the information sources above, the following fields for each AUM were captured in the comprehensive AUM Database:

1. Mine ID, Mine claim, Mine name, Map ID and aliases;
2. The mine latitude and longitude;
3. Reclamation status;
4. Results of the gamma survey (above or below background gamma concentrations, and if gamma readings above ten-times background concentration were observed);
5. Number of residential structures within 200-feet, and from 200-feet to 0.25-miles from the mine feature, and a description of the residential structure;
6. Observed water sources within 0.25 miles, and within 4-miles of the mine feature;
7. Descriptions of waste piles onsite, and dimensions of waste piles;
8. Number of adits, open adits, pits and shafts located at the feature;
9. If the site was accessible, or inaccessible due to terrain constraints or site access issues;
10. Site features description, and notes from the Site Screen surveys;
11. Production values from historical operation of the mine; and
12. Hazard scores for groundwater, soil, air, surface water, and the combined hazard score for each mine.

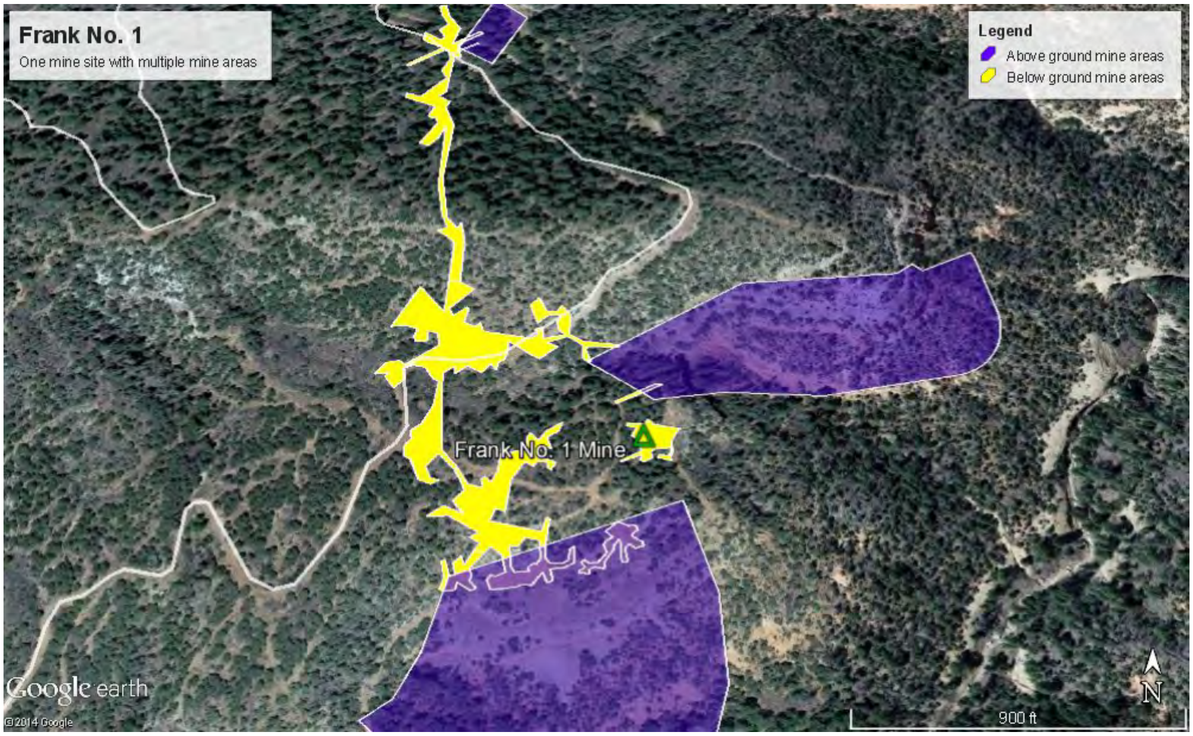
Using Geographic Information Systems (GIS), geospatial data layers were generated illustrating the number of AUMs that have the features (or range in features) for the fields provided above.

The number of mines within the Navajo Nation can be counted in different manners, as summarized below:

Source	Description	Number of mine claims/mine sites[87]
2007 AUM Atlas	520 mine claims identified in the 2007 Atlas	520 mine claims
	602 mine sites represented by the 520 mine claims	602 mine sites
2014-2018 Five-Year Plan[88]	520 mine claims from the Atlas, not including NECR and Churchrock claims, plus three additional claims (Crownpoint South Trend, Chavez and Isabella)	521 mine claims
	602 mine sites from the Atlas, plus 6 additional AUMs identified during Weston Site Screen Reports	608 mine sites
USEPA (numbers presented within this Initial White Paper)	520 mine claims from the Atlas, plus 3 new claims identified during Weston Site Screen Reports	523 mine claims
	602 mine sites, plus 6 new mine sites identified during Weston Site Screen Reports	608 mine sites[89]

Based on the compilation of various data-sources, 523 AUM mine claims were identified on the Navajo Nation in the AUM Database. Mine claims often include multiple AUMs that share one production record. For example, “Frank No. 1” mine claim below includes three AUM sites:

87 PowerPoint entitled “Navajo AUM Mines overview 8.7.15” prepared by Lina Reeves, USEPA.
88 Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation, 2014.
89 Note that Weston conducted Site Screen Reports on nine sites that were not mines, which are not included in the 608 mine sites noted above.



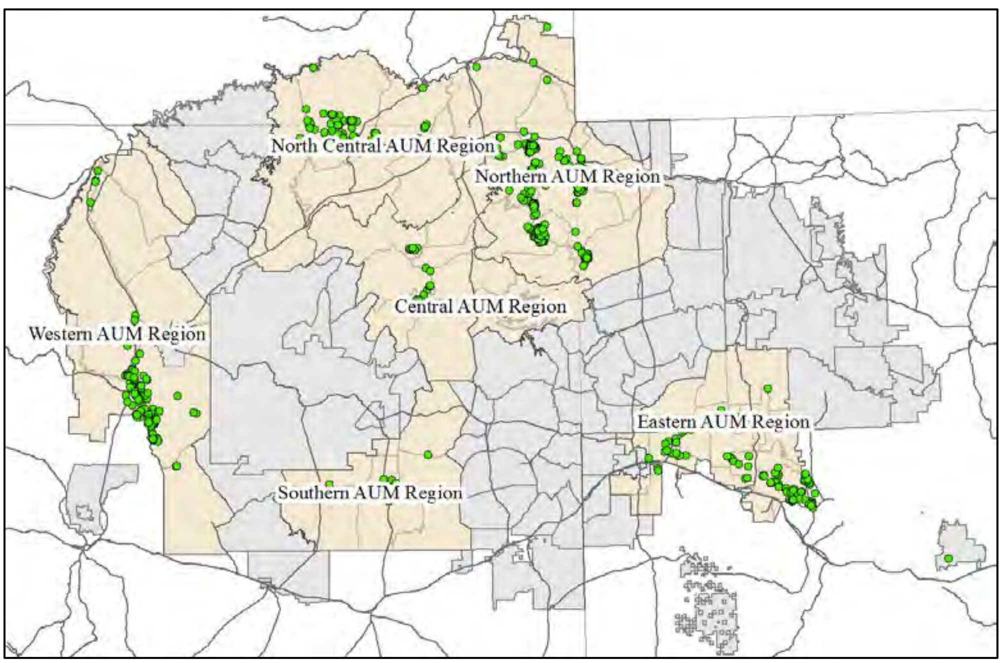
Frank No. 1 Mine Claim with three AUM Sites (illustrated in Purple)[90]

The AUM Database identified 523 AUM mine claims (consisting of the 608 mine sites included in the January 2013 Five Year Plan, plus an additional nine sites screened by Weston, for a total of 530 Screen Reports). A comparison of some of the statistics presented in the January 2013 Five Year Plan *vs*. statistics from the AUM Database is provided in the table that follows:

[90] PowerPoint presentation entitled "Navajo AUMs" USEPA, October 2014.

Comparison of 2013 Five-Year Plan with Additional Mine Information Provided in this Initial White Paper		
Parameter (Five Year Plan includes "Mine Claims", AUM Database includes "AUMs")	**2013 Five-Year Plan Summary (Mine Claims)**	**AUM Database (Mine Sites)**
Number (mine claims or mine sites)	521	608
Number scanned for gamma radiation	474	577
Number with gamma radiation levels above 2 times background	402	493
Number with gamma radiation levels above 10 times background	226	261
Number not scanned due to access issues	47	54
* USEPA cites 523 AUM claims based on 520 mine claims in the 2007 AUM Atlas plus 3 new mines identified in mine claim screens.[91]		

The 523 AUM mine claim locations identified in the more current AUM Database are illustrated in the figure that follows.[92]



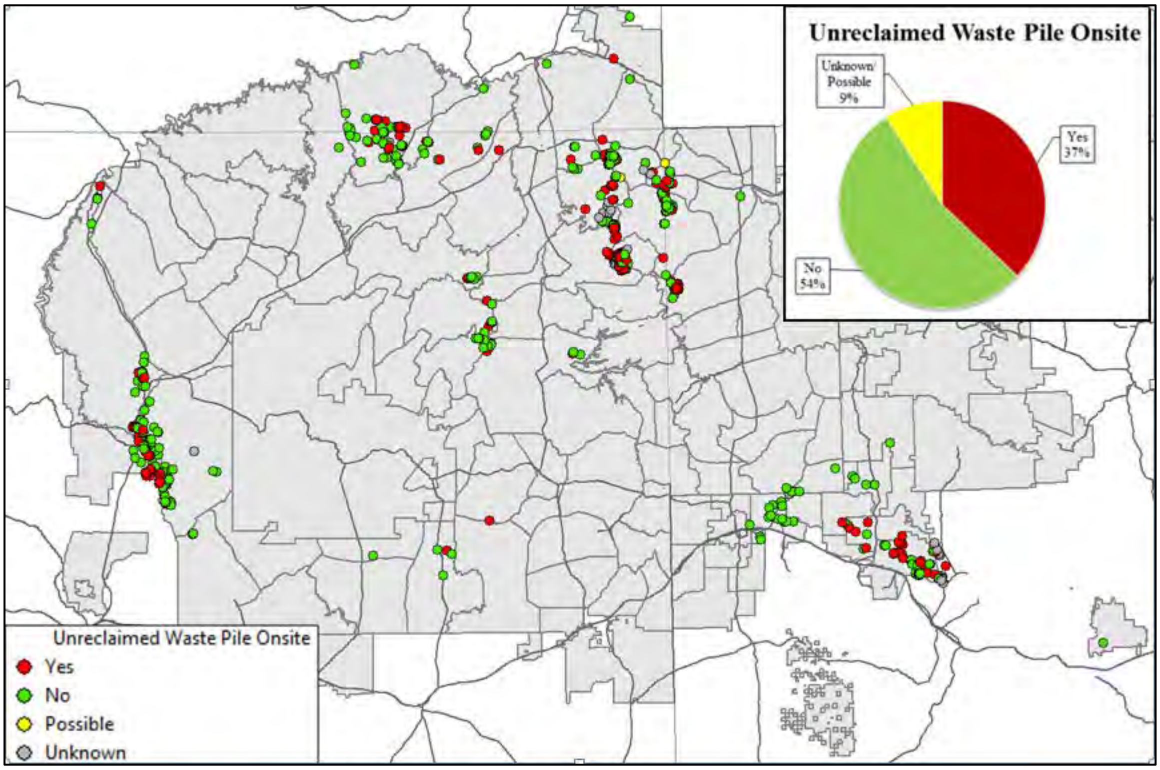
Distribution of 523 AUM mine claims on the Navajo Nation within AUM Regions (illustrated in tan)

---

91 PowerPoint presentation entitled "Navajo AUMs" USEPA, October 2014.

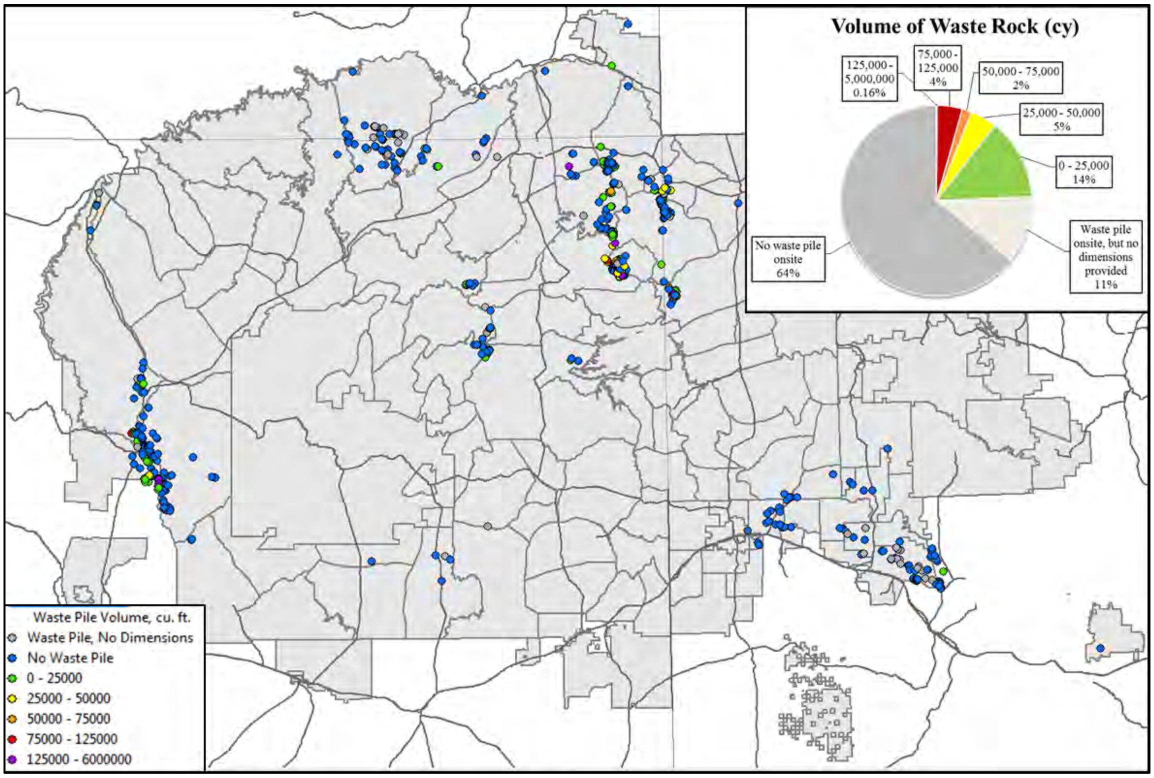
92 Note that the following figures illustrate 608 locations associated with the 523 AUM mine claims. Also note that these figures include nine sites surveyed by Weston that are not mines. Because many of the AUMs are located in close proximity, there may not appear to be 617 locations illustrated on the maps, due to overlap.

Based on the information provided in the current AUM Database, and using GIS, the following statistics and figures were generated to illustrate the characteristics of AUMs on the Navajo Nation. A select number of fields are provided below, with a map and pie chart illustrating statistics, and the locations of the AUMs.[93]

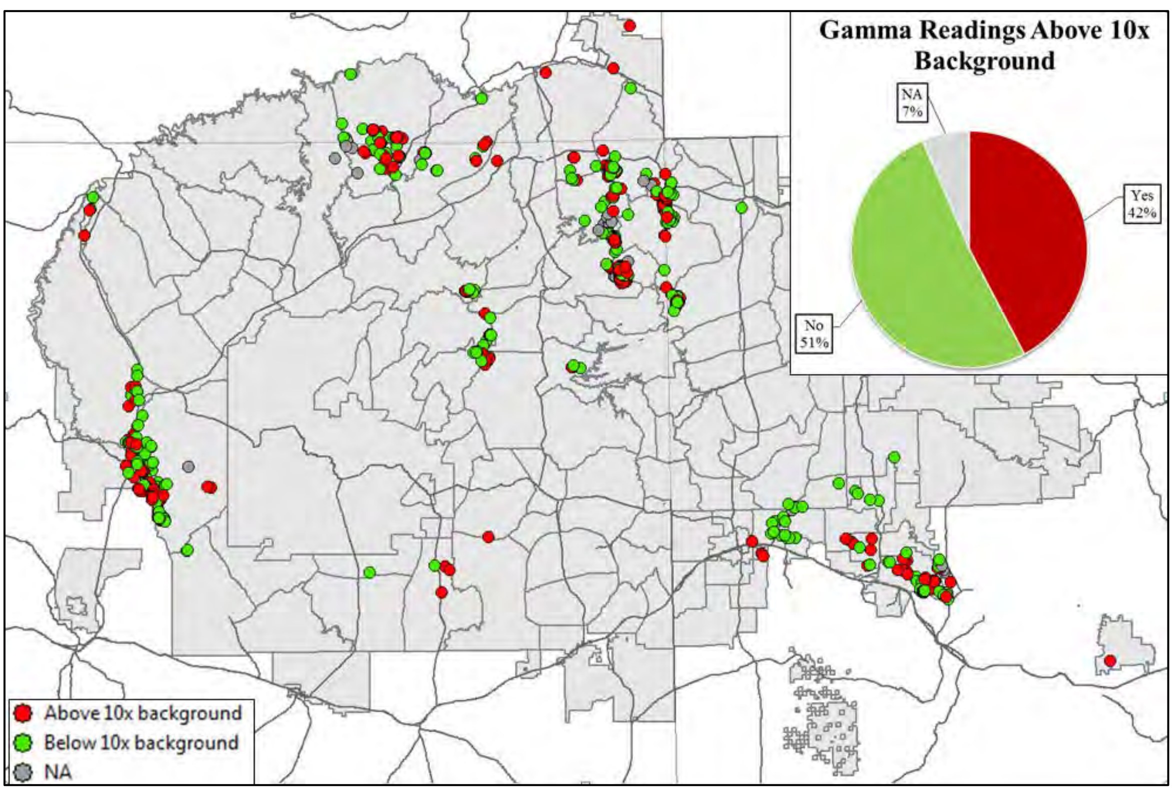


Pie Chart and Graph Illustrating AUMs with Un-reclaimed Waste Piles Onsite (“Yes” indicates an un-reclaimed waste pile is present. As noted above, reclamation did not address radiological hazards.)

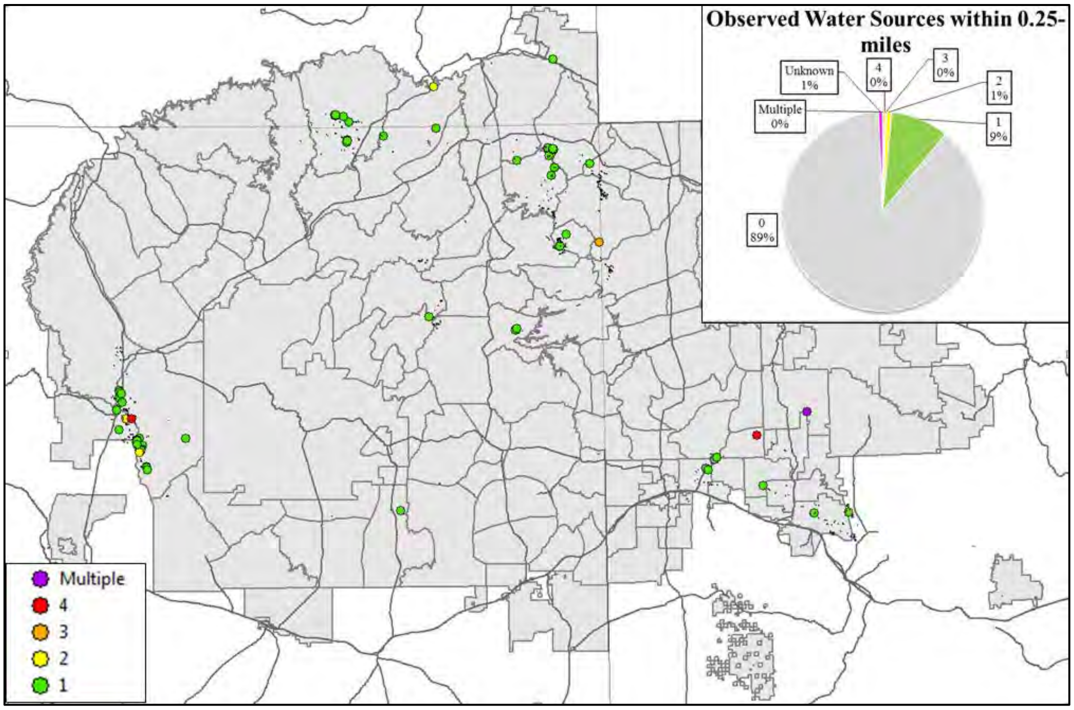
[93] This data is preliminary and further study is needed to verify accuracy.



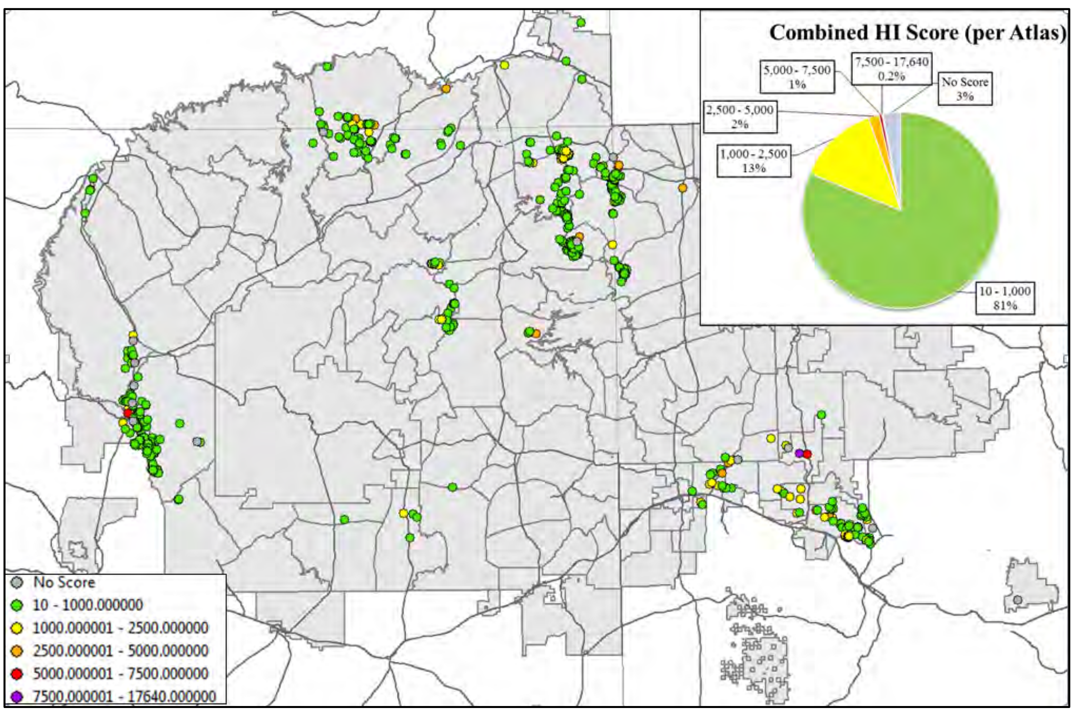
Pie chart and Graph Illustrating Volume of Waste Rock at AUM locations (note the map only illustrates AUMs with waste rock onsite)



Pie Chart and Map Illustrating Maps with Gamma Readings about 10X background



Pie Chart and Map Illustrating Number of Livestock and Human Drinking Water Sources within 0.25-miles of AUM Structures



Pie Chart and Map Illustrating the Combined Hazard Index Score (groundwater, soil, air, surface water) from 2007 AUM Atlas[94]

[94] Abandoned Uranium Mines and The Navajo Nation, Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data August, 2007 (Table 4 - Table 9).

The magnitude of the uranium mining legacy on the Navajo Nation is reflected by the following statistics based on 523 mine claims:

1. 409 mine claims have gamma radiation levels above 2-times background, 261 of which have gamma radiation levels above 10-times background;

2. Per the 2007 Atlas HI scoring system;

    a. 58 mine claims are located within 1,320-feet of a livestock or human drinking water well;

    b. 198 mine claims are located within 200-feet of a structure (for air pathway and soil exposure points); and

    c. 518 mine claims are located within one-mile of a perennial or intermittent surface water source;[95]

3. 17 mine claims have a residential structure within 200-feet;

4. 38 mine claims have gamma radiation levels above 2-times background, with a residential structure located within ¼-mile.

The above statistics are compelling and reflect the magnitude of the uranium problem within the Navajo Nation. As noted earlier, waste rock consolidation and capping or construction of an encapsulated cell has been completed at 3 of the 523 AUM mine claims (Skyline Mine, the Cove Transfer Stations and Section 32 Mine) and substantial cleanup actions have been conducted at two others (NECR and Quivira Mines), leaving the vast majority as a continuing risk to the Navajo people and preventing full use and enjoyment of their land including most of the high priority mines identified by the USEPA and NNEPA.

---

95 Tables 4 through 9 of the 2007 Atlas indicate a total surface water score of 160 for every AUM evaluated.

3.0 NAVAJO FUNDAMENTAL LAW PERTAINING TO URANIUM CONTAMINATION AND NAVAJO NATION COUNCIL'S ESTABLISHMENT OF THE URANIUM COMMISSION

Cleanup of radiologically-impacted waste rock within the Navajo Nation must be undertaken in ways consistent with inherent beliefs of members of the Navajo Nation. In November 2002, the Navajo Nation Council passed a resolution amending Title 1 of the Navajo Nation Code to recognize the fundamental laws of the Diné. As shown in the excerpt that follows, §5 to Chapter I (Foundation of the Diné, Diné Law and Diné Government) resolved that Diné natural law "*declares and teaches*" that the earth is "*sacred*" and that, "*it is the duty and responsibility of the Diné to protect and preserve the beauty of the natural world for future generations.*" An excerpt of §5 to Chapter I is shown below.

<u>§ 5. Nahasdzáán dóó Yádiłhił Bits´ą́ądę́ę́´ Beehaz´áanii -Diné Natural Law,</u>

Dine Natural Law declares and teaches that:

A. The four sacred elements of life, air, light/fire, water and earth/pollen in all their forms must be respected, honored and protected for they sustain life; and

B. The six sacred mountains, Sisnaajini, Tsoodził, Dook´o´oosłííd, Dibé Nitsaa, Dził Na´oodiłii, Dził Ch´ool´í´í, and all the attendant mountains must be respected, honored and protected for they, as leaders, are the foundation of the Navajo Nation; and

C. All creation, from Mother Earth and Father Sky to the animals, those who live in water, those who fly and plant life have their own laws and have rights and freedoms to exist and;

D. The Diné have the sacred obligation and duty to respect, preserve and protect all that was provided for we were designated as the steward for these relatives through our use of the sacred gifts of language and thinking; and

E. Mother Earth and Father Sky is part of us as the Diné and the Diné is part of Mother Earth and Father Sky; The Diné must treat this sacred bond with love and respect without exerting dominance for we do not own our mother or father.

F. The rights and freedoms of the people to the use of the sacred elements of life as mentioned above and to the use of land, natural resources, sacred sites and other living beings must be accomplished through the proper protocol of respect and offering and these practices must be protected and preserved for they are the foundation of our spiritual ceremonies and the Diné life way; and

G. It is the duty and responsibility of the Diné to protect and preserve the beauty of the natural world for future generations;

3.1 Fundamental Law and Cleanup of AUM Waste

The desire of the Navajo Nation's to remove hazardous substances from the Navajo Nation was formalized in a 2002 NNEPA memorandum which stated that "*all petroleum-contaminated soil must be removed from the Navajo Nation*."[96] This statement can extend to uranium-impacted materials because of its greater toxicity and greater potential human health impacts compared to petroleum constituents.

The desire of the Navajo people to remove uranium-impacted material from the Navajo Nation was also articulated by Stephen B. Etsitty, former Executive Director of NNEPA:

> *"It is the policy of the Navajo Nation that all 'hazardous substances,' including uranium, must be removed from the Navajo Nation and disposed on lands outside of the territorial boundaries of the Navajo Nation. This policy has been in force and effect during my tenure as Executive Director of the Navajo EPA."*
>
> "*This policy has arisen from the Navajo Nation's long experience with the legacy of uranium mining within the Navajo Nation. The policy is designed to reduce the impact of uranium mining waste on significant customs and cultural values that are unique the Navajo people. The policy is also the result of the risks to human health and the environment from uranium mine waste*." [97]

Perry Charley, a member of the Navajo Nation and Program Manager of the Uranium Education Program at Diné College, describes that, for the Navajo, the land signifies Mother Earth to which the Navajo are tied both before and after their birth.[98] In order to establish and maintain these ties, the Navajo bury their umbilical cords in the land where they were born on the Reservation.[99] The Navajo believe that Mother Earth is "*a place of emergence, a place of birth, a place of ties, where eventually [the Navajo] will be put back into - - into its fold, into its arms, into the dirt*."[100] The Navajo cannot leave their sacred homeland.[101]

---

96 NNEPA, October 29. 2002. Memorandum from NNEPA to "Whom it May Concern," entitled "No Landfarms Allowed on the Navajo Nation."
97 June 2011, Declaration of Stephen B. Etsitty. Page 1.
98 Deposition of Perry Charley, May 17, 2011, p 106.
99 Deposition of Perry Charley, May 17, 2011, p. 107.
100 Deposition of Perry Charley, May 17, 2011, p. 107.
101 Deposition of Perry Charley, May 17, 2011, p. 108.

A 2003 paper co-authored by Perry Charley[102] discusses the Navajo people's belief that the legacy of uranium mining and milling on the Navajo Nation disrupts the "*balance and harmony between humans and nature*," and uranium itself is regarded by the Navajo as "*the antithesis to the sacred corn pollen that is used to bless the lives of the Navajo*."[103] As explained by Perry Charley, the Navajo have four sacred elements - the air, land, water, and fire - and when they are in equilibrium the Navajo live in a harmony referred to as "Ho'zoo, the beauty way."[104] The contamination of the Navajo land caused by uranium mining has resulted in a displacement of harmony which the Navajo believe results in illnesses and sickness. As a result of the contamination of their homeland, Mr. Charley believes that there is "*[a] great disharmony, a great impact. That's what the Navajos are facing right now*."[105]

In October, 2007, the Navajo Nation confirmed its desire that hazardous substances be removed from its land. More specifically, according to an October 23, 2007 Congressional Hearing,[106] "*[a]ll contaminated materials in all UMCTRA[107] sites throughout Navajo Indian Country should be excavated and disposed of properly outside of Navajo Indian Country in the same manner as being done at Moab and has been done at other UMTRCA sites*." Further, the President of the Navajo Nation, Joe Shirley, on the thirtieth anniversary of the uranium mill tailings impoundment failure at the Church Rock uranium mill site (2009), discussed the Navajo Nation's "*stated goal of removing all uranium contaminated materials completely out of Navajo Indian Country*." While stating that he believed "*U.S. EPA has been convinced to remove all Northeast Church Rock site contaminated materials off of tribal lands*," Mr. Shirley discussed the challenges that remain for the Navajo:[108]

---

[102] Psychological Effects of Technological/Human-Caused Environmental Disasters: Examination of the Navajo and Uranium, American Indian and Alaska Native Mental Health Research, Journal of the National Center, Volume 11, Number 1, 2003.

[103] Psychological Effects of Technological/Human-Caused Environmental Disasters: Examination of the Navajo and Uranium, American Indian and Alaska Native Mental Health Research, Journal of the National Center, Volume 11, Number 1, 2003.

[104] Deposition of Perry Charley, May 17, 2011, p. 107-108.

[105] Deposition of Perry Charley, May 17, 2011, p. 108-109.

[106] Hearing Goals Presented by Navajo Government Witnesses, Congressional Hearing, October 23, 2007.

[107] Roux Associates notes that the Lukachukai and Tse Tah mine sites are not governed UMTCRA; however Navajo Nation's position regarding the removal of such contaminated materials from Navajo Nation land is pertinent.

[108] Remarks of President Shirley on 30th Anniversary of Uranium Mill Tailings Spill, July 16, 2009.

"the USEPAs' apparent preferred remedy for the Northeast Church Rock site is to transfer the great bulk of the contaminated materials to the UNC Superfund site and take only a small portion of such materials, those labeled as 'principle threat waste,' to a disposal facility outside of Navajo Indian Country."

Mr. Shirley added:[109]

"the Navajo Nation will not look at this as a final solution, even for the Northeast Church Rock site. With the support of the local residents and the Navajo Nation EPA we will continue to press for ways to reduce the volume and toxicity of the Northeast Church Rock materials that remain in Navajo Indian Country."

The Navajo Nation's desire to remove hazardous substances from its land was further affirmed by the United Nations in 2007 in a Declaration on the Rights of Indigenous Peoples, "*States shall take effective measures to ensure that no storage or disposal of hazardous materials shall take place in the lands or territories of indigenous peoples without their free, prior and informed consent.*"[110] Removing uranium-impacted material from Navajo Nation land is also supported by recent (2009) USEPA approval to excavate and dispose off-reservation uranium-contaminated soil at five home sites on the Navajo Nation Indian Reservation.[111]

Furthermore, as summarized below, federal law, federal regulations and USEPA policy require that the Navajo Nation's policy of requiring the removal hazardous substances from the Navajo Nation be considered in deciding upon a final cleanup option for contamination within the Navajo Nation. More specifically:

---

109 Remarks of President Shirley on 30th Anniversary of Uranium Mill Tailings Spill, July 16, 2009.

110 United Nations Declaration on the Rights of Indigenous Peoples, 61/295, Resolution adopted by the General Assembly, 107th plenary meeting, September 13, 2007.

111 Request for Time-Critical Removal Action at the Northeast Church Rock Residential Site, McKinley County, New Mexico, Navajo Nation Indian Reservation, dated April 18, 2007 and approved July 23, 2009.

1. Under federal law (CERCLA), the President must consult with the governing body of an Indian tribe "*before determining any appropriate remedial action*;"[112]

2. Similarly, the NCP requires the USEPA to consider the Navajo Nation's preferences for cleanup actions when selecting a cleanup alternative on Navajo lands. Specifically, in selecting a cleanup alternative, the USEPA must consider both "state acceptance,"[113] including "*the state's position and key concerns related to the preferred alternative and other alternatives*," and "community acceptance," including "*which components of the alternatives interested persons in the community support, have reservations about, or oppose*;"[114]

3. Accordingly, the USEPA developed a policy in 1984 for consultation with Indian tribes. More specifically, the EPA Policy for the Administration of Environmental Programs on Indian Reservations, dated November 8, 1984 (the "1984 Policy"), states that the "keynote" of the USEPA's efforts to protect human health and the environment on Indian reservations "*will be to give special consideration to Tribal interests in making Agency Policy, and to insure the close involvement of Tribal Governments in making decisions and managing environmental programs affecting reservation lands*." The 1984 Policy includes the following principles (among others):

   (a) "The Agency stands ready to work directly with Indian Tribal Governments on a one-to-one basis (the "government-to government" relationship), rather than as subdivisions of other governments;"

   (b) "The Agency will recognize Tribal Governments as the primary parties for setting standards, making environmental policy decisions and managing programs for reservations, consistent with Agency standards and regulations;" and

112 42 U.S.C. §§ 9604 and 9626.
113 As defined in the NCP (40 CFR § 300.5), the term "state" includes Indian tribes except where specifically noted. Section 126 of CERCLA provides that the governing body of an Indian tribe shall be afforded substantially the same treatment as a state with respect to certain provisions of CERCLA.
114 40 CFR § 300.340(e)(9) and (f).

(c) *"The Agency, in keeping with the federal trust responsibility, will assure that Tribal concerns and interests are considered whenever EPA's actions and/or decisions may affect reservation environments."*

The USEPA recently confirmed the 1984 Policy in its May 2, 2011 Policy on Consultation and Coordination with Indian Tribes (the "2011 Policy"). The 2011 Policy states that the "*1984 Policy remains the cornerstone for USEPA's Indian program and 'assure[s] that tribal concerns and interests are considered whenever USEPA's actions and/or decisions may affect' tribes*."[115] Further, the 2011 Policy recognizes that "response actions" under CERCLA are "*normally appropriate for consultation if they may affect a tribe*."

3.2 The Diné Uranium Remediation Advisory Commission and Master Plan of Operation

In January 2015, the 23rd Navajo Nation Council introduced a resolution establishing the Diné Uranium Remediation Advisory Commission (the "Commission") which was established as an advisory commission in the Executive Branch of the Navajo Nation Government. The Uranium Commission's purpose is to, "*study and reach conclusions about the impacts of uranium mining and uranium processing on the Navajo Nation and to make recommendations to the President of the Navajo Nation and to the Navajo Nation Council for policies, laws and regulations to address those impacts*." The Master Plan of Operation for the Commission further clarified that the Uranium Commission was to review and make recommendations on issues including but not limited to, "*remediation and restoration of areas contaminated by past uranium mining and uranium process; appropriate technologies to address wastes, including potential locations to dispose and isolate uranium wastes*." The Commission is guided by traditional Navajo governance and planning including the Naabik'iyati "talking things out" and the Fundamental Laws of the Diné. The Commission's goals are to develop, "*measureable objectives and devising practical and publically acceptable plans for remediation*[116] *and restoration*[117] *of the lands to protect current and*

---

115 USEPA Policy on Consultation and Coordination with Indian Tribes, May 2, 2011.

116 "Remediation" is defined by the Uranium Commission Master Plan as, "the permanent closure of uranium mining and uranium processing sites, waste piles and associated buildings for the purposes of eliminating or substantially reducing releases of radioactive and toxic substances to the air, land and water in such ways as to prevent or substantially minimize human exposure to such substances now and for future generations. 18 N.N.C.§1302.D.

117 "Restoration" is defined by the Uranium Commission Master Plan as, "returning land, vegetation, water and air to its original state, or as close to its original state as is technologically possible, without regard to cost, in accordance with the duty of the Diné to protect and preserve the beauty of the natural world for future generations, as set forth in 1 N.N.C.§205.G.

future generations from uranium mining and process wastes, in accordance with the Fundamental Laws of the Diné."

On April 24, 2015, the 23rd Navajo Nation Council formally resolved[118] to establish the Diné Uranium Remediation Advisory Commission as, "*an advisory commission in the Executive Branch of the Navajo Nation Government*" with the same goal as stated in the January 2015 proposed resolution presented above. On May 4, 2015, President Ben Shelly signed the resolution establishing the Commission.

On July 9, 2015 the 23rd Navajo National Council passed a resolution, "*Relating to the Naabik'iyati committee; adopting the plan of operation for the Diné uranium remediation advisor commission.*" The resolution reiterated that the purpose of the Diné Uranium Commission is to "*study and reach conclusion about impacts of uranium mining and uranium processing on the Navajo nation and to make recommendations to the President of the Navajo Nation and to the Navajo Nation. Attached to the resolution as Exhibit B is the 'Diné Uranium Remediation Advisory Commission Master Plan of Operations' which states that the Commission may review and make recommendations on the "remediation and restoration of areas contaminated by past uranium mining and uranium processing; appropriate technologies to address wastes, including potential locations to dispose and isolate uranium wastes.*" The Commission "*is guided by Fundamental Laws of the Diné to find ways to return leetso to its natural balance with Mother Earth so that it does not harm the sacred elements or the sacred lina[119] of the human beings and animal and plant people that exist on Mother Earth.*"[120]

3.3 Navajo Nation's Department of Justice Position Regarding Institutional Controls

Institutional Controls (ICs) are measures used to restrict or limit exposures to hazardous substances in conjunction with a selected cleanup alternative. §300.430 of the NCP (Remedial investigation/feasibility study and selection of remedy) states that,

118 CAP-14-15. Resolution of the Navajo Nation Council. 23rd Navajo Nation Council, First year, 2015, an action relating to law and order, resources and development and naabik'iyati' committees and Navajo Nation Council; amending 2 N.N.C.§3580 to create a Diné uranium remediation advisory commission.

119 "lina", or life, is energy that is in all life forms and sentient beings.

120 "Leetso" literally means "yellow dirt" or "yellow cake," referring to the appearance of uranium as observed by Navajos.

(a) USEPA expects to use a combination of methods, as appropriate, to achieve protection of human health and the environment. In appropriate site situations, treatment of the principal threats posed by a site, with priority placed on treating waste that is liquid, highly toxic or highly mobile, will be combined with engineering controls (such as containment) and institutional controls, as appropriate, for treatment residuals and untreated waste.

(b) USEPA expects to use institutional controls such as water use and deed restrictions to supplement engineering controls as appropriate for short- and long-term management to prevent or limit exposure to hazardous substances, pollutants, or contaminants. Institutional controls may be used during the conduct of the remedial investigation/feasibility study (RI/FS) and implementation of the remedial action and, where necessary, as a component of the completed remedy. The use of institutional controls shall not substitute for active cleanup measures (e.g., treatment and/or containment of source material, restoration of ground waters to their beneficial uses) as the sole remedy unless such active measures are determined not to be practicable, based on the balancing of trade-offs among alternatives that is conducted during the selection of remedy.

Note the use of land use controls and/or institutional controls are not included in Navajo CERCLA.

The USEPA prepared a draft document on the process of implementing ICs in Indian country as part of cleanup projects addressing the unique circumstances to IC implementation in Indian country such as tribal sovereignty, cultural traditions, and property jurisdiction. In response to this draft, the Navajo Nation Department of Justice issued the following statement regarding its position on the use of "institutional controls" with reference to cleanups of sites containing hazardous substances as that term is defined in the Navajo Nation CERCLA, 4 N.N.C §2101 et seq.[121]

[121] May 21, 2013 Navajo Nation Department of Justice, Office of the Attorney General, "Comments on Draft Handbook Implementing Institutional Controls in Indian Country."

> *The NNDOJ is generally opposed to the use of "institutional controls" as part of a permanent environmental remedy at any site on the Navajo Nation. The NNDOJ does, however, support the use of such institutional controls as temporary means of protecting local populations from existing threats to human health or the environment. The NNDOJ will work with all responsible parties in implementing such temporary institutional controls provided that such parties acknowledge to the NNDOJ in writing their understanding of, and, agreement to abide by this principle.*

May 21, 2013 Comments on Draft Handbook Implementing Institutional Controls in Indian Country

The Navajo Nation DOJ concluded that, "*Diné Fundamental Law views Mother Earth as a sentient being, and likewise there are spirit forces to be addressed when modern industrial society unearths a powerful monster that was sleeping. Accordingly, we must observe the nayee and observe its ways. We may not be able to negotiate with it, but we must address its destructive force. Just as the Hero Twins, and particularly Monster-Slayer did, we must know this monster and deal with it appropriately. Depending upon its behavior, it may or may not be possible to accept natural attenuation*."

Shortly after, USEPA issued its Handbook on "Implementing Institutional Controls in Indian Country," [122] intended solely for USEPA employees addressing (a) jurisdiction, (b) land records and title concerns, and (c) working with tribes. The Handbook encourages regional USEPA staff "*to consult tribes about ICs early in the cleanup process when ICs are being evaluated, selected, and/or whenever the tribe has interest that may be affected. Consultation should occur regardless of the tribe's liability status*." The Handbook also directs USEPA employees to "*evaluate all forms of knowledge sharing, including lifeways and sacred practices that may affect the use of an IC*." Notwithstanding the above, nothing in USEPA's Handbook restricts in any way the use of ICs as part of a final cleanup option.

3.4 Summary of Diné Fundamental Law Pertaining to Uranium Contamination

Justice Robert Yazzie, former Chief Justice of the Navajo Nation Supreme Court points out that "*any discussion of uranium waste remediation alternative must employ indigenous knowledge. The two major prongs of an approach are the indigenous knowledge approach and indigenous perspectives of methodology*." Indigenous knowledge embodies Navajo belief in "*the idea of hozho, and although it is the ideal state of everything being in good relation and harmony with everything else, the ideal does carry with it the aspiration of establishing good interdependent relationships among all sentient beings (including animals*

[122] USEPA, "Implementing Institutional Controls in Indian Country," Office of Site Remediation Enforcement, Office of Enforcement and Compliance Assurance, November 2013.

and matter)-it is a form of consciousness or a traditional environmental impact statement. Therefore, the hozho paradigm is a traditional Navajo approach to life situations to assess situations, plan, implement and assess, despite any resulting adversity." Justice Yazzie outlined the following five components for a methodology to address uranium contamination:

1. The idea or aspiration is 100% cleanup and killing or taming of Leetso, the Yellow Monster;

2. The methodology aims at a higher goal or ideal than practices such as institutional control or natural attenuation;

3. Any methodology must be consistent with Natural Law principles of the Diné Fundamental Law that require 100% cleanup to attain Siihasin or resilience in the face of the Leetso nayee or life obstacle;

4. There does not appear to be a consensus on measurement, so criticism of that approach is reasonable, and we are more concerned about qualitative rather than quantitative outcomes; and

5. If there is a continual focus on "how" then nothing will be done or achieved-ignoring a Monster at large is not an acceptable means to an end.

According to Diné Fundamental Law, everything has life (linà[123]), including uranium. Uranium is sometimes referred to as the Yellow Monster or *Leetso* which literally means "yellow dirt" or yellow cake" (referring to the appearance of uranium as observed by Navajos). The Yellow Monster), is a force of disharmony, fear, and evil. The fear can be both actual (health impacts from exposure to ionizing radiation) and perceived (waste rock remnants and past experiences). The uranium monster only knows how to take life, and there are no Navajo songs, dances, or ceremonies to dispel this evil. Ideally, the Yellow Monster should be returned to the depths of Mother Earth from which it was taken; however, the mine shafts which remain have insufficient void space into which to place the monster, and

[123] Linà, or life, is energy that is in all life forms and sentient beings. As such, all of life has the capability and capacity of hozhooji (good or goodness) or hashkeji (bad or badness) that much me balanced to achieve beneficial results. It is this balance, known by the Navajo word hózhó that the Commission must strive to achieve in carrying out its functions and in its consideration of cleanups and policies related to uranium mining and uranium processing on the Navajo Nation.,

groundwater within and surrounding these shafts could be adversely impacted by placing uranium waste into these shafts, thus allowing the monster to escape once again. Therefore, since the monster cannot be killed by returning it to Mother Earth, it must be banished (sent off of the Navajo Nation) or at least tamed (contained).

Notwithstanding the Navajo Nation's desire to remove uranium-impacted material from Navajo land, under some circumstances the use of engineered containment cells to manage AUM waste on Navajo land may be within the framework of Navajo Fundamental Law which is based on experience rather than a set of rules. According to paragraph 9 of the Uranium Commission's Master Plan of Operation, decisions by the Commission to reach conclusions about appropriate technologies are "*guided by Fundamental Laws of the Diné to find ways to return leetso to its natural balance within Mother Earth so that it does not harm the sacred elements or the sacred line of the human beings and animal and plant people that exist on Mother Earth (N.N.C§205).*" Such a decision appears to be consistent with paragraph 10 of the Master Plan Operation by using the "*traditional characteristics of each of the Four Direction: (i) Nitsahakees, for intuition, discovery and thinking of the East (2 N.N.C§110(N); Nahat'a, or planning (2 N.N.C.§110(M), and nahat'a or Naat'aahji,*[124] *or the talk of planning, of the south to carefully examine and involve all interests and knowledge holders in the process; jinà to implement thought and consensual plans actively and for good results in the West (2N.N.C.§110(g); and Sihasin, or reflection and reconsideration, to assess the result of thinking, talking, planning and doing, of the North (2 N.N.C. §110(T). Naabik'iyai (2 N.N.C.§110(M).*"

Decisions on how to address uranium impacts should be based on critical thinking and evaluation of the problem from different angles, including consideration of impacts to local populations. For example, in areas where uranium radiation is not aggressively reaching out to kill (i.e., less than ten times background) or where few people live, engineered containment cells specifically designed and inspected/maintained to keep the monster contained may sufficiently tame the monster until it chooses to leave (which may take millennia). In other instances disposal of AUM waste off of Navajo land may need to be considered such as in mountainous terrain where containment cells may be difficult to

[124] Naat'aahji is the process of talking and planning, to carefully examine and involve all interests of all people and knowledge holders in the process of decision making. Navajo leadership philosophy considers this one of the key traits of good governance and good leadership.

construct, monitored or maintained or where AUM waste is in close proximity to communities or water bodies.

Critical thinking is needed to determine when uranium may need to be consolidated and managed in containment cells on the Navajo Nation and when it may need to be transported off the Navajo Nation. Factors to be considered in this critical thinking are the rights and protection of the Navajo people and Mother Earth, adherence to Navajo Fundamental law, technical and cost considerations, and the selection criteria set forth in the NCP [40 CFR Part 300.430(e)(7)(iii)] and in Title 4, Navajo Nation Code Chapter 17 (the Navajo Nation CERCLA). Further, where containment cells are used on Navajo Nation land that limit the Navajos' ability to use and enjoy its land and essentially take the land from the Navajo, compensatory land to the Navajo Nation may need to be considered. Decisions about cleanup alternative selection should be open and transparent to all stakeholders with no hard feelings (Nayleeh) to provide a harmonious relationship (Hoozho) throughout the decision making process. A transparent process and inclusion of compensatory land as part of the cleanup are consistent with Articles 28 and 29 of the United Nations' Declaration on the Rights of Indigenous Peoples which state that, "*States shall establish and implement….a fair, independent, impartial, open and transparent process, giving due recognition to indigenous peoples' laws, traditions, customs and land tenure systems…*" and "*Indigenous peoples have the right to redress, by means that can include restitution….for the lands, territories and resources which they have traditionally owned or otherwise occupied or used…and which have been…damaged without their free, prior and informed consent.*" [125]

[125] United Nations Declaration on the Rights of Indigenous Peoples, 61/295, Resolution adopted by the General Assembly, 107th plenary meeting, September 13, 2007.

4.0 URANIUM CONTAMINATION ON THE NAVAJO NATION, ASSESSMENT TECHNIQUES AND DATA NEEDS

The purpose of uranium contamination assessment at AUMs is to identify, quantify and understand the impacts of uranium contamination to human health and Mother Earth so that the risks can be understood and measures to stabilize and/or cleanup such contamination can be identified and implemented. Information from such assessment can also be used to prioritize additional assessment and/or cleanup activities based on various factors including the severity of radiological impacts, proximity to groundwater, surface water and residential populations and potential for further uranium transport to environmental media.

Accurate and timely assessment of uranium impacts on the Navajo Nation is integral to the protection of human health and Mother Earth. Radionuclides are odorless, tasteless, and cause significant and long term health effects. To protect the Navajo people from ongoing exposure to uranium, uranium impacts from AUMs must be completely assessed and delineated so any continued exposure pathways can be addressed.

AUM assessment consists of the following components:

- Site location, mine history (claim number, owner, operator) and setting;
- Status of reclamation or cleanup;
  - Adits
  - Waste rock
  - Pits
  - Shafts
  - Other debris or mine features
- Radiological impact assessment; and
- Identification of uranium migration pathways and potential receptors.

From October 2008 through November 2011,[126] Weston Solutions, Inc. (Weston) completed "Site Screen Reports" of the 523 AUM mine claims[127] to provide baseline information about known AUMs.[128] The purpose of these Site Screen Reports was to "*ascertain the status and location of the identified AUM site, and record all immediate site information associated with the mine site*." The Weston reports contain information available from USEPA AUM databases including production information, and claim/operator information that was available in historical documentation. GPS based ground surveys were conducted in the vicinity of each AUM that was accessible, and maps illustrating gamma concentrations above background conditions were included in each Site Screen report. Off-site gamma readings for each mine were collected to evaluate results against naturally occurring gamma radiation levels in the vicinity of the AUM. Finally, field observations of mine features (such as rims, pits, adits, portals and prospects) were also mapped using GIS data, and were photographed and described. Additionally, Weston inspectors, in some instances estimated the volume of waste rock present onsite, noted any reclamation that had been conducted at the AUM (including the integrity/mechanism of reclamation), and made note of surrounding features such as residences, structures, or drinking water sources.

Example Site Screen Report figures generated for the Martin Mine and George Simpson No. 1 Mine (51) and Flag No. 1 Mine (511) in the Round Rock Chapter are provided below.

[126] Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation—Five Year Plan Summary report, January 2013.

[127] 523 AUM mine claims were surveyed from 2008 through 2011, totaling 608 mine sites plus 9 sites that are not AUMs (Yellow Canyon, Yazzie / Arviso Farm, Vendor Stand Near Highways 89 and 160, Sloan Piles / Tailings, Area Across From Mine #230, Gold Springs Wash Area, Cove Wash, Tom House Dump Pile Area, and Cameron Roads Area.) USEPA "Navajo AUM mines overview 8.7.15" PowerPoint presentation.

[128] The Site Screen Reports specify that site screen reports were conducted for mines "*that were included in the USEPA CERCLIS database, all the site listed in the 2008 AUM GIS Report Issued by the USACOE and USEPA and AUM site on allotment lands associated with the Navajo Nation, and any and all AUM sites not listed in any database located on Navajo lands*."

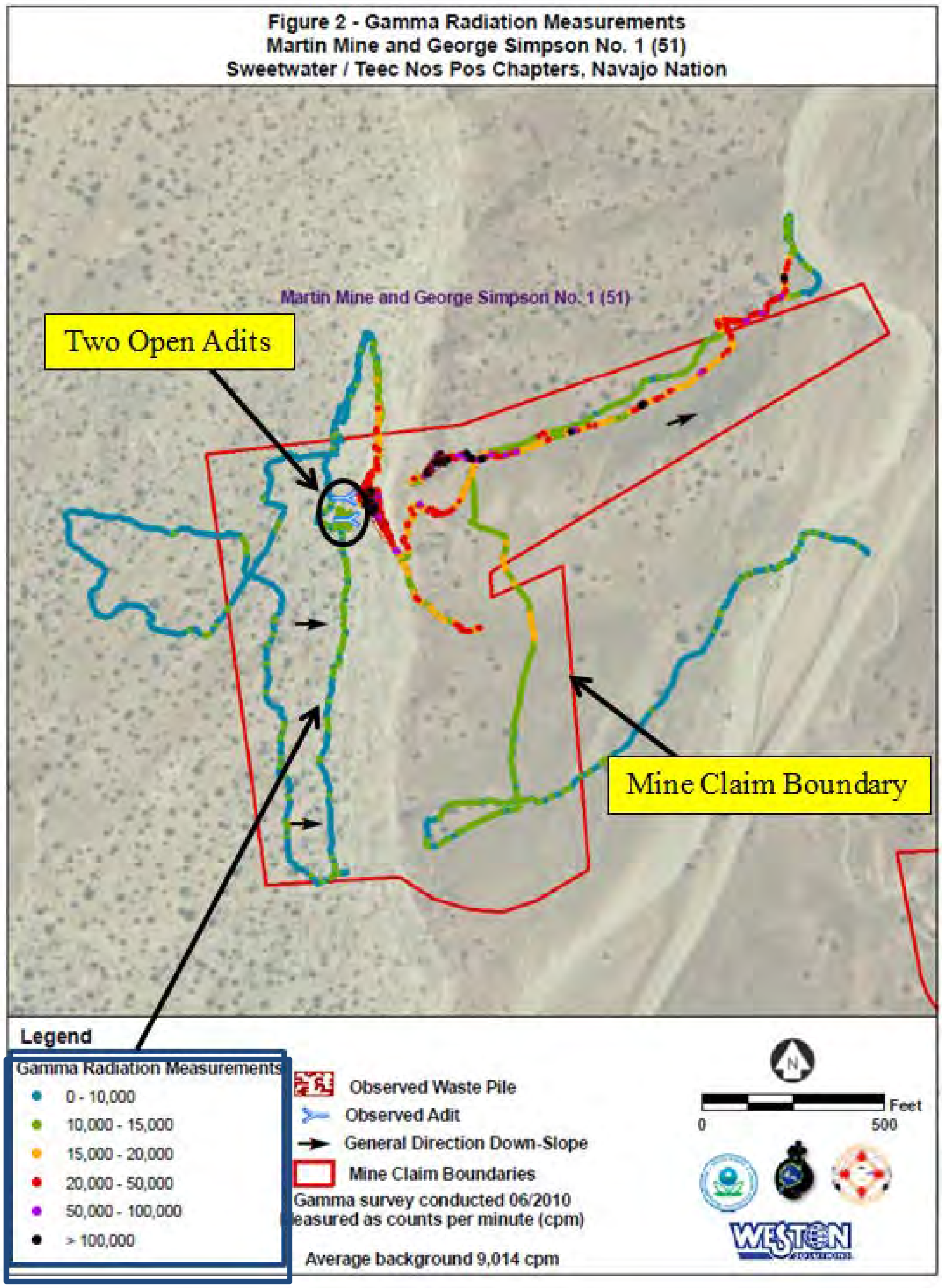


Figure from Site Screen Report for the Martin Mine and George Simpson No. 1 AUM Site

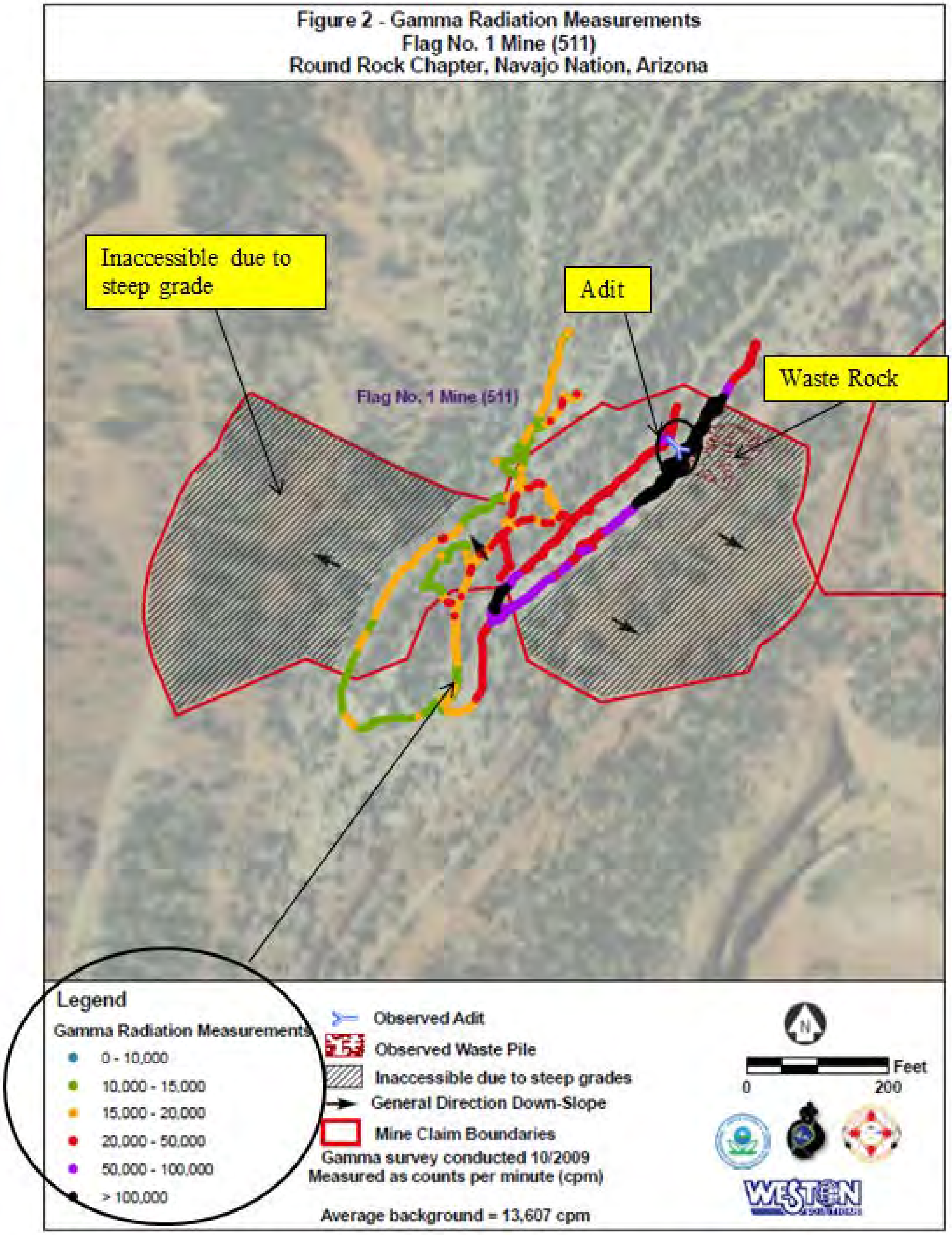


Figure from Site Screen Report for the Flag No. 1 Mine AUM Site

As discussed previously in this Initial White Paper, information contained in the Weston Site Screen reports was incorporated into the AUM Database compiled for this Initial White paper.

This chapter reviews the uranium assessment techniques used to determine the nature and extent of radiological impacts at AUMs along with data needs to further determine such impacts.

4.1 Radiological Assessment Techniques

Radiological methods are organized into the categories listed below and discussed in further detail in the subsections that follow:

1. Assessment of Radiological Impacts at the Surface:

    (a) Aerial Radiological Surveys

    (b) GPS based gamma surveys

2. Assessment of Radiological Impacts at Depth

3. Radiological Assessment of other Matrices

    (a) Groundwater and water supply

    (b) Surface water

    (c) Contaminated structures

    (d) Air and Dust

4.1.1 Assessment of Radiological Impacts at the Surface

Assessment of surficial radiological impacts is divided into two broad categories (a) aerial surveys and (b) GPS-based surveys. Aerial surveys provide radiological data across large areas of land and can be used to identify smaller areas for more detailed evaluation. GPS-based surveys are conducted at land surface and provide greater resolution of radiological impacts.

<u>Aerial Radiological Surveys</u>

Aerial radiological surveys are the most practical and appropriate assessment technique to identify uranium impacts over large areas of land. Aerial surveys are ideal for large scale baseline surveys and to identify targeted areas requiring additional higher spatial resolution measurements. Special processing can identify locations of AUMs, waste rock and/or spoils, transfer stations, high natural uranium deposits, and other activities potentially related to uranium mining by identifying locations above background levels.[129]

Helicopters or aircraft equipped with acquisition platforms that include flight path systems, gamma detectors, and data acquisition systems and various software packages are capable of performing accurate radiological surveys.[130] The surveys collect spectra which are analyzed for a variety of parameters indicative of uranium contamination:

(a) Total gamma count rate (counts per second) which measures gamma activity from all terrestrial sources after subtracting "background data" contributions from radon, cosmic and aircraft sources. Background conditions are usually established by measuring gamma counts over a body of water or from greater than 3,000-feet above ground;[131]

(b) Exposure rate (micro Roentgen per hour);

(c) Uranium concentration (pCi/g); and

(d) Excess bismuth^{214}activity[132] (which is an indicator of uranium ore deposits and/or uranium mines).[133]

Detector pods or "packs" for airborne spectroscopy consist of sodium iodide (Na[Ti]) scintillation detectors (for example, RSX-4 Units provided by Radiation Solutions Inc., or comparable detectors designed for airborne spectroscopy).[134] Depending on the desired data density, flight swaths can be flown at various altitudes (ranging from 150-feet to higher then 500-feet), and flight path width (horizontal spacing) can be adjusted based on data needs (see example figure illustrating flight paths at Ambrosia Lake, below).[135,136]

---

129 US Department of Energy, August 2001. An Aerial Radiological Survey of Abandoned Uranium Mines in the Navajo Nation. USDOE/NV/11718--602

130 US Department of Energy, August 2001. An Aerial Radiological Survey of Abandoned Uranium Mines in the Navajo Nation. USDOE/NV/11718--602

131 USEPA Aerial Radiological Surveys Ambrosia Lake Uranium Mines, Ambrosia, NM, August 2011.

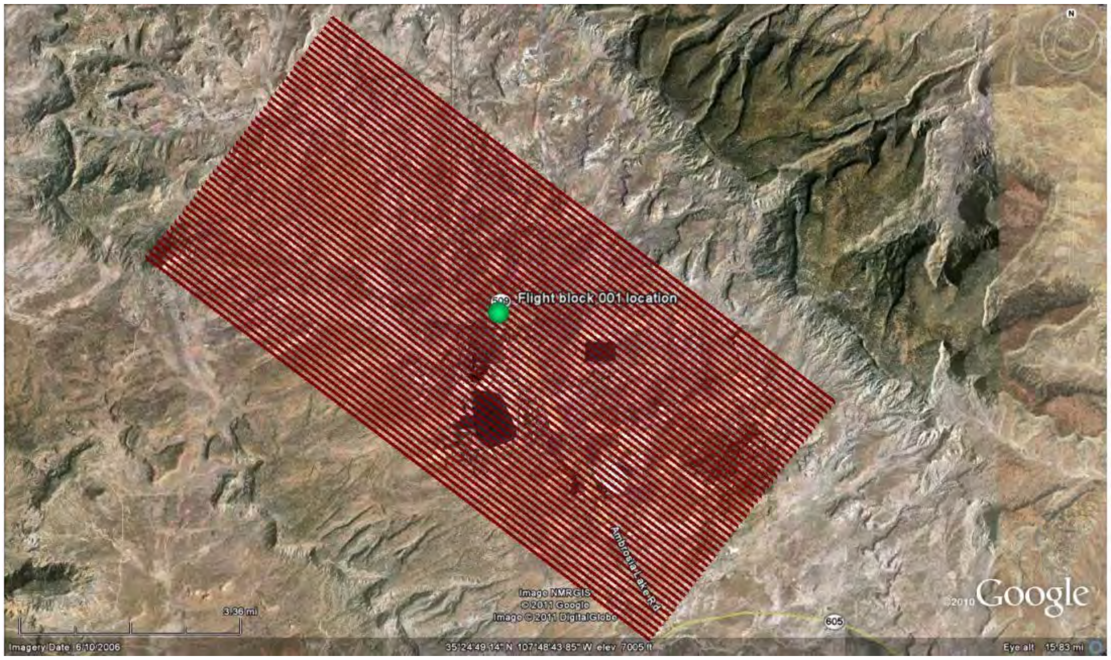
132 Bismuth 214 is a decay product of radium-226.

133 US Department of Energy, August 2001. An Aerial Radiological Survey of Abandoned Uranium Mines in the Navajo Nation. USDOE/NV/11718--602

134 USEPA Aerial Radiological Surveys Ambrosia Lake Uranium Mines, Ambrosia, NM, August 2011.

135 US Department of Energy, August 2001. An Aerial Radiological Survey of Abandoned Uranium Mines in the Navajo Nation. USDOE/NV/11718--602

136 http://airborneaspect.com/uploads/4/8/5/5/48555863/casestudy.pdf

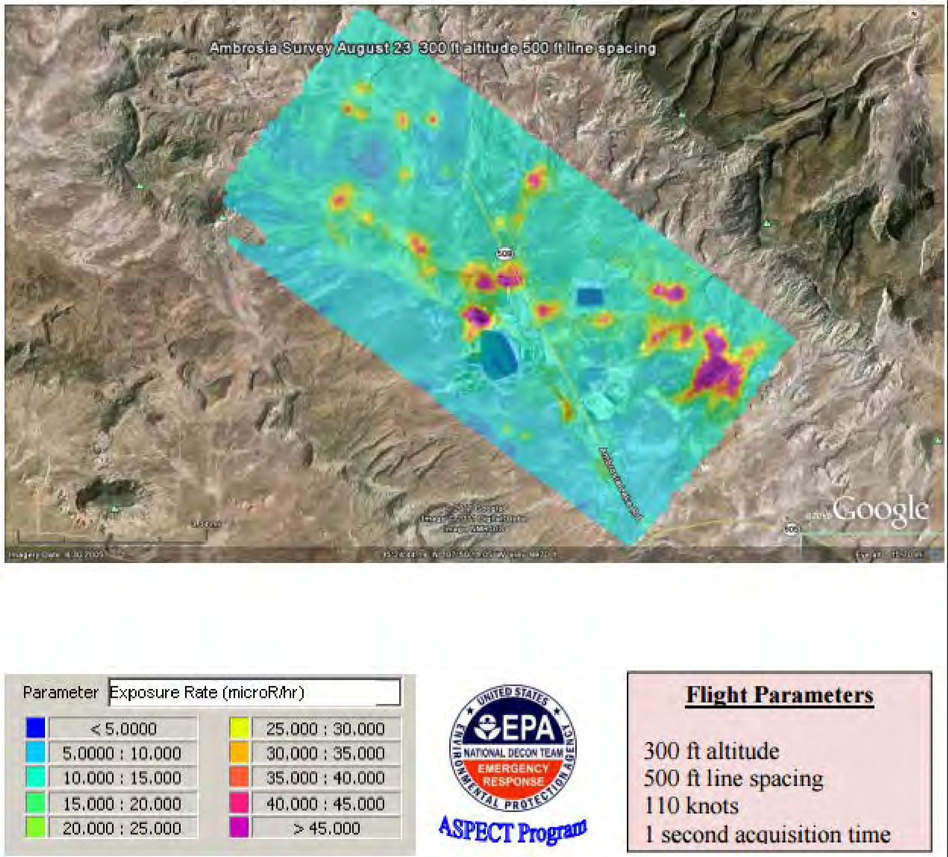


Flight lines for Aerial Survey Conducted in 2011 at Ambrosia Lake, NM[137]

Parameters are recorded in real time during the flight patterns, and various software systems (such as RadAssist, ENVI®, and ASPECT) collect data which are linked to the geographic location of the plane/helicopter. Using GIS software, contoured images can be generated for each of the parameters (total count rate, exposure rate, uranium concentration and excess bismuth^{214}). An example of an Exposure Rate Contour from an aerial survey conducted at Ambrosia Lake is provided in the figure that follows.

[137] USEPA Aerial Radiological Surveys Ambrosia Lake Uranium Mines, Ambrosia, NM, August 2011.

Image 3: Exposure Rate Contour
Ambrosia Survey
August 23, 2011



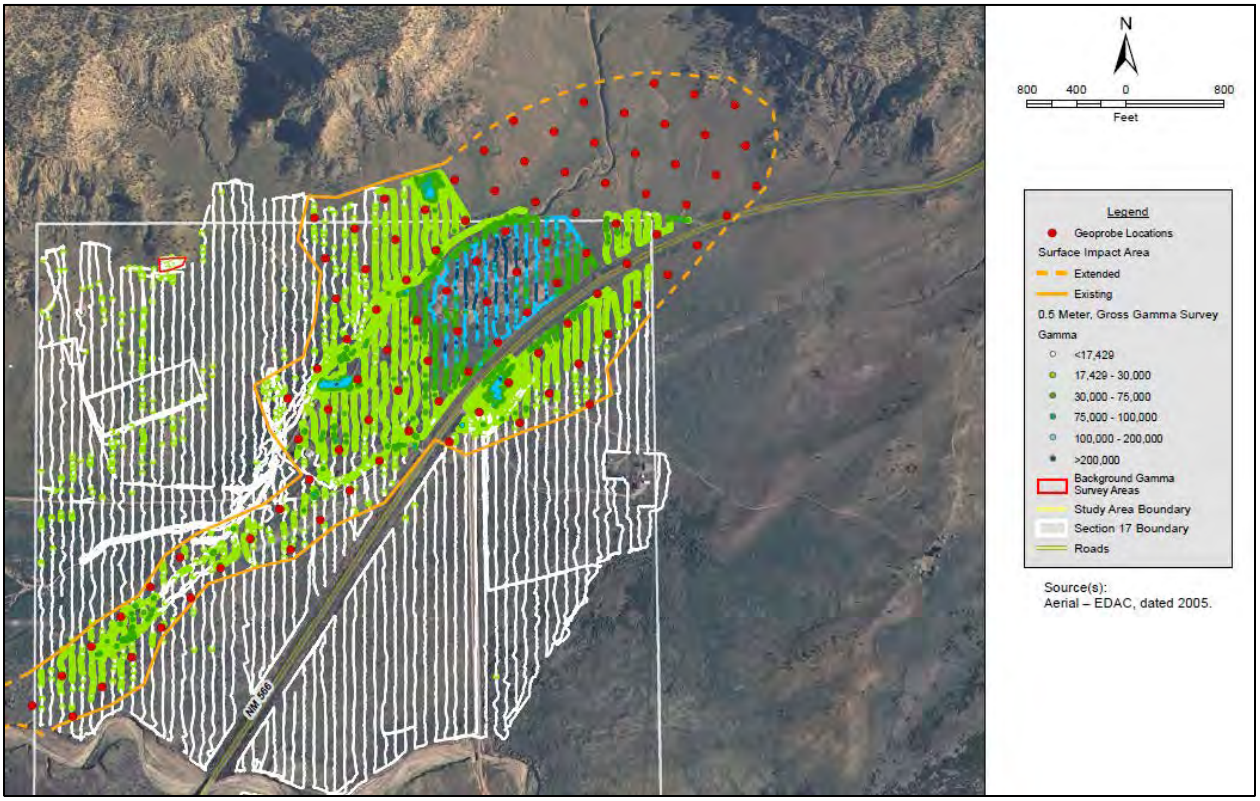
Exposure Rate Contour for Aerial Survey Conducted in 2011 at Ambrosia Lake, NM[138]

GPS-Based Gamma Surveys

GPS-Based gamma surveys assess surface soil radiation by identifying gamma-emitting radionuclide concentration anomalies. GPS based gamma surveys are conducted using sodium iodide (Na[I]) (often 2-inch by 2-inch, or 4-inch by 4-inch) scintillation detectors with a ratemeter/scaler coupled to a GPS Receiver and datalogger. NaI detectors are typically used to cover large areas quickly—they are sensitive, rugged and inexpensive (such as the Ludlum 2221 Portable Scaler/Ratemeter coupled with a Ludlum 44-10 2"X2" NaI crystal scintillation detector).[139] Transects are spaced at various intervals depending on the size of the area to be surveyed, and can be conducted using all-terrain vehicles or walking carrying equipment in backpacks. Survey transects may need to be adjusted due to accessibility/obstructions. To

[138] USEPA Aerial Radiological Surveys Ambrosia Lake Uranium Mines, Ambrosia, NM, August 2011.
[139] Ludlum Measurements, Inc. http://www.ludlums.com/component/virtuemart/area-monitoring-5/detectors-57/alpha-beta-gamma-gm-62/radiation-detector-185-detail?Itemid=0

establish appropriate scaling of gamma impacts, it is important to establish "background conditions." Often, multiple surveys conducted at offsite locations may be necessary to establish background conditions. An example of a GPS based ground survey is provided below from a survey conducted at the Old Churchrock Mine Site. A photograph is also provided showing a ground gamma survey conducted by Weston



Gross Gamma Survey of the Old Church Rock Mine Site[140]

[140] Draft Site Characterization Due Diligence Plan Phase 2 Old Church Rock Mine prepared for Uranium Resources Incorporated by Intera, August 30, 2012.

GPS gamma ground survey conducted during Weston Site Screen Reports[141]

Keith, et. al,[142] notes the following limitations in measuring uranium by portable survey instruments:

> Several limitations are associated with the measurement of uranium by portable survey instruments. First, the uranium must be present on the surface of the material being surveyed. Since uranium decays by emission of α particles, which travel only short distances in materials, any uranium that is imbedded in the surface being surveyed will be partially or completely masked. Secondly, when performing surveys, it must be possible to place the detector very close to the surface being surveyed (i.e., approximately one-quarter of an inch) (DOE 1988, 1994a), and uneven surfaces that are unintentionally touched can tear the detector window, disabling the instrument. Additional information is available in MARSSIM (2000) on the use and usefulness of field survey instruments.

In addition to measuring gamma-emitting radionuclide concentration anomalies, Ra-226 concentrations in surface soils can be estimated from a site-specific correlation between RA-226 concentrations in soil and the gamma count-rate data. This is obtained by making integrated count-rate measurements at several locations and correlating this count rate with the RA-226 concentration as determined from surface soil samples taken at the locations, via GeoProbe samplers, or manual sample collection.[143] A linear regression between these

---

141 Federal Actions of Address Impacts of Uranium Contamination in the Navajo Nation, Five Year Plan Summary report, January 2013.

142 Keith S, Faroon O, Roney N, et. al. "Toxicological Profile for Uranium. Atlanta (GA): Agency for Toxic Substances and Disease Registry; February 2013: http://www.ncbi.nlm.nih.gov/books/NBK158797/

143 Draft Site Characterization Due Diligence Plan Phase 2 Old Church Rock Mine prepared for Uranium Resources Incorporated by Intera, August 30, 2012.

parameters allows conversion of the gamma count rate maps to Ra-226 in soil.[144] Sample locations are typically chosen to span the range of gamma count rates encountered at a given location. The linear regression correlation from gamma ray intensity to RA-226 concentration is summarized in the equation below:

$$Y = mX + b$$

where,
Y = soil concentration in pCi/gm,
m = slope, pCi/gm/cpm
X = count rate (the mean) in cpm
b = constant, y intercept

Linear regression of Gamma Ray Intensity to Ra-226 Soil Concentrations[145]

It is also important to verify that real time ground surveys are collecting data in accordance with established performance parameters such as gamma energy, identity of surrogate or progeny nuclides, identity of interfering gamma rays, conditions and contexts of soils (including soil moisture, topography, and measurement geometry), and contaminant distribution (deviation from uniform distribution, lateral heterogeneity, etc.).[146]

4.1.2 Assessment of Radiological Impacts at Depth

Where uranium impacts extend beyond surface impacts, additional methods can be employed to assess uranium contamination at depth. Samples are obtained using conventional drilling rigs along with smaller GeoProbe sampling equipment. Sample cores obtained are scanned using a shielded core analyzer with NaI probes. As illustrated in the figure below, a shielded core analyzer can be assembled using lead bricks to eliminate "shine" from surrounding surface soil conditions so that accurate gamma measurements can be determined from the soil core.

---

144 Draft Site Characterization Due Diligence Plan Phase 2 Old Church Rock Mine prepared for Uranium Resources Incorporated by Intera, August 30, 2012.

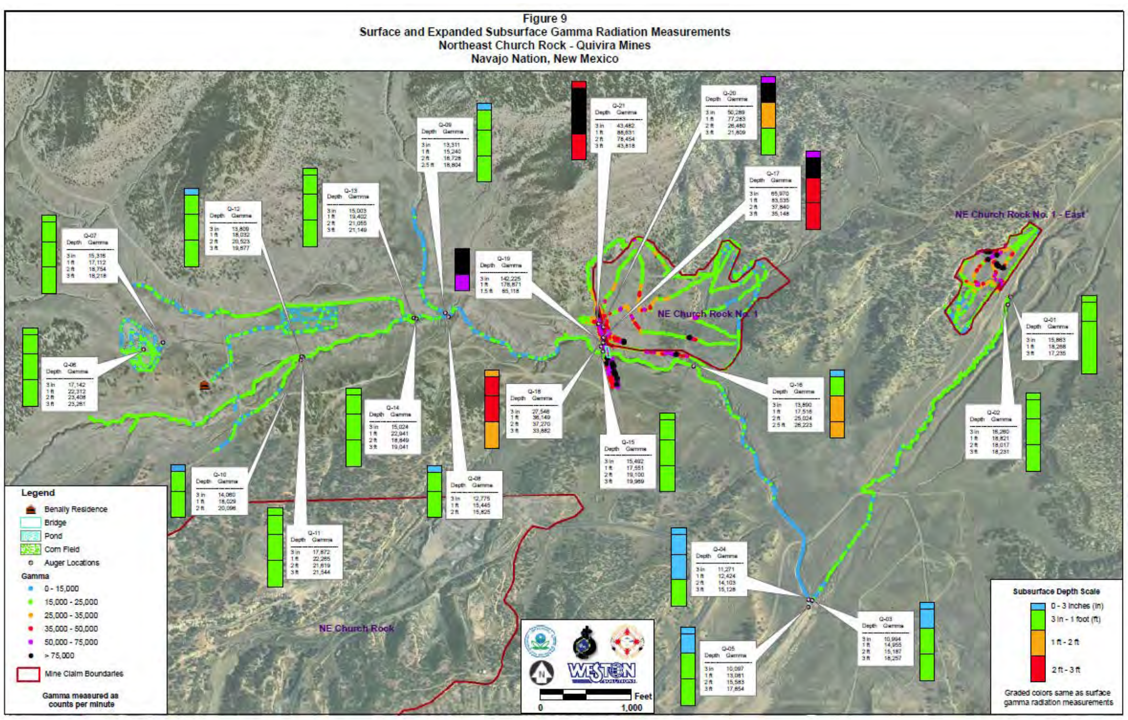
145 Removal Evaluation Workplan Church Rock Sites 1 and 1E Phase II Volume III: Standard Operating Procedure, December 2010. http://yosemite.epa.gov/R9/SFUND/R9SFDOCW.NSF/92ac13b328517708882574260073faee/fb270cf5c8582b718825786400755ab6/$FILE/350180%20SOPs%201-10%20-%206Dec2010.pdf

146 Interstate Technology Regulatory Council, February 2006. Real-Time Measurement of Radionuclides in Soil: Technology and Case Studies.

Shielded Core Analyzer with Lead Bricks

As with gamma based GPS surveys, core increments representing the range of the scaler counts may need to be analyzed for Ra-226 to correlate gamma counts with Ra-226.

The figure which follows (of the Northeast Churchrock Mine) illustrates gamma reading data over various depth intervals:



Northeast Churchrock Gamma Readings at 0 – 3 ft depths
Gamma readings (counts/minute) ranging from > 75,000 (black) to 0 (Blue)

4.1.3 Radiological Assessment of Other Matrices

Assessment techniques exist for other environmental matrices including groundwater, surface water, contaminated structures, dust and particulates as discussed in the subsections which follow.

Groundwater and Surface Water

Radiological impacts of groundwater and surface water include the presence of uranium, radium and radon. Their physical properties are summarized in the tables provided in **Appendix A** and in the text which follows.

Radium:

Radium in water exists primarily as a divalent ion (Ra^{+2}). The solubility of radium salts generally increases with increasing pH with radium sulfate and carbonate species having low solubility. Alternatively radium nitrate, chloride, and iodate are very soluble in water although it is typically controlled by adsorption and desorption reactions at solid-liquid interfaces which are in turn influenced by pH and co-precipitation of minerals. [147]

Uranium:

Uranium exists in five oxidation states (+2, +3, +4, +5 and +6) however, only the +4 and +6 states are stable. Tetravalent uranium forms hydroxides, hydrated fluorides, and phosphates of low solubility. Hexavalent uranium is the most stable with the most commonly occurring state being uranium hexafluoride (UF6). Major compounds of uranium include oxides, fluorides, carbides, nitrates, chlorides, acetates, and others. The chemical form determines its solubility as summarized in the table provided in **Appendix A**.[148]

Radon

Radon (^{222}Rn) is a naturally occurring radioactive noble gas that is part of the ^{238}U decay chain, and is the daughter of ^{226}Ra. As radium decays, radon is formed and is released into small air or water-containing pores between soil and rock particles. Radon solubility in water is relatively low and with its short radioactive half-life of 3.825 days, much of it will decay before it can be released from groundwater. Radon solubility is relative low (230 cm^3/L of water at 200C) and due to its relatively short half-life, much of it will have decayed to polonium and other non-volatile progeny before groundwater reaches the surface.

[147] ATSDR for Radon: http://www.atsdr.cdc.gov/toxprofiles/tp144.pdf
[148] ATSDR for Uranium: http://www.atsdr.cdc.gov/toxprofiles/tp150.pdf

However, any remaining radon in solution can be released to ambient air once it is encountered. In areas where groundwater has high levels of radon, release from groundwater may significantly affect ambient air levels. [149]

Under aerobic conditions, uranium is soluble while radium is less soluble and often associated with and found on clay and mineral coatings. Radon gas occurs in either dissolved phase or as tiny bubbles that partition into air during various use of radon-impacted water such as during showering or washing.[150]

Surface runoff from AUMs also carries uranium impacted suspended solids from waste piles which can impact surface water supplies. Therefore, radiological measurements of surface water include analyzing both dissolved and suspended solid concentration and radioactivity.)[151,152]

Automated surface water samplers with rain gauges are the preferred method to collect surface water samples for subsequent analysis of various radionuclides.

Analytical methods for measuring uranium in water as well as other environmental media are summarized in the table provided in **Appendix A** as compiled by Keith ET. al.[153]

According to the USEPA,[154] ^{226}Radium, ^{228}Radium and Uranium have 17, 8 and 15 approved methods for measuring these radionuclides in drinking water, respectively as summarized in tables provided in **Appendix A**.

149 ATSDR for Radon: http://www.atsdr.cdc.gov/toxprofiles/tp145.pdf
150 Wirt, Laurie. Radioactivity in the Environmental—A Case Study of the Puerco and Little Colorado River Basins, Arizona and New Mexico. USGS, 1994.
151 Wirt, Laurie. Radioactivity in the Environmental—A Case Study of the Puerco and Little Colorado River Basins, Arizona and New Mexico. USGS, 1994.
152 Graf, J.B. et. al. Streamflow Transport of Radionuclides and Other Chemical Constituents in the Puerco and Little Colorado River Basins, Arizona and New Mexico. USGS Water Supply Paper 2459, 1996.
153 Keith S, Faroon O, Roney N, Et Al. "Toxicological Profile for Uranium. Atlanta (GA): Agency for Toxic Substances and Disease Registry; February 2013: http://www.ncbi.nlm.nih.gov/books/NBK158797/table/T32/?report=objectonly
154 Compendium of USEPA Approved Analytical Methods for Measuring Radionuclides in Drinking Water, June 1998: https://www.orau.org/ptp/PTP%20Library/library/DOE/Misc/radmeth3.pdf

Contaminated Structures

Some Navajo community members used materials such as wood, rocks, and pieces of metal from AUMs contaminated with uranium in building homes, hogans and ceremonial structures.[155] Materials used have included:

- Chunks of ore and waste rock used for foundations, walls, or fireplaces;
- Tailings mixed into cement used for foundations/floors; and
- Cinderblocks contaminated by tailings.[156]

A photograph of a contaminated structure is provided below.

Photograph of Contaminated Structure[157]

Assessment of contaminant structures can include (a) testing radon impacts to indoor air (discussed in the section below), and (b) gamma surveys to determine if a structure is contaminated. Similar to GPS based gamma surveys described in the sections above, an important first step when conducting a gamma survey of a potentially impacted structure is to determine appropriate background levels. Radiological surveys of building interiors are conducted using NaI scintillating detectors, and concentrations within the structure are compared to background conditions to assess if uranium impacts exist.

155 2014 GAO Report http://www.navajolaw.org/2014_docs/Uranium_GAO_Report.pdf
156 USEPA Contaminated Structures Stakeholders Conference, April 2013. http://www.epa.gov/region9/superfund/navajo-nation/pdf/stakeholders/2013/usepa-structures-update2013.pdf
157 USEPA Contaminated Structures Stakeholders Conference, April 2013. http://www.epa.gov/region9/superfund/navajo-nation/pdf/stakeholders/2013/usepa-structures-update2013.pdf

Between 2008 and 2012, USEPA and NNEPA surveyed 878 structures and, when found to pose a health risk, USEPA demolished and rebuilt or provided financial compensation for the structures. In total, 34 structures were addressed either through financial compensation or with a rebuilt home and contaminated soil was removed from eighteen yards. Construction of an additional eight homes was also anticipated to be completed by the fall of 2014. According to the Second, Five-Year Plan, NNEP will scan up to 100 homes per year and will refer those that show elevated levels of radiation to USEPA for follow-up actions.[158]

Air and Dust

Air and dust (particulates) monitoring in the vicinity of AUMs with uranium impacts is necessary to ensure adequate protective measures are being taken to limit human exposure to radionuclides. Wind erosion of contaminated AUM spoils suspended in dust or soil particles can spread substantial amounts of uranium contamination to nearby residences. Air monitoring can provide an estimate of the potential radiation doses to workers and/or the public via (a) particulate matter, or (b) inhalation of radon gas.

Particulate matter filter sampling to assess radioactive dust is performed with high volume air samples (such as Graseby-Anderson high volume air samples),[159] and ratemeters (such a Ludlum Model 4 ratemeter, with scintillation probe).[160] Filters are screened using the ratemeter prior to submitting to certified laboratories for analysis (via Mass Spectrometry). Site specific conditions at the time of sampling are also typically recorded, such as recent precipitation data and wind speed.

---

158 USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, "Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation," 2014.

159 March 6, 2008. Particulate Matter Sampling and Correlations to Wind Tunnel Durst Samples from the Cave Hills Harding, Co., South Dakota. US Forest Service. Website: http://uranium.sdsmt.edu/Downloads/PM%20Results%20Final%2003-06-08.pdf

160 Removal Evaluation Work Plan Church Rock Sites 1 and 1E Phase II Volume II: Standard Operating Procedure, December 2010. Website: http://yosemite.epa.gov/R9/SFUND/R9SFDOCW.NSF/92ac13b328517708882574260073faee/fb270cf5c8582b718825786400755ab6/$FILE/350180%20SOPs%201-10%20-%206Dec2010.pdf

Graseby-Anderson High Volume Air Sampler[161]

Additionally, air monitoring may need to be conducted in residences in areas with uranium impacts to screen for the presence of radon gas, a decay product of uranium. Radon exposure can occur via contact with contaminated well water used in dish washing, showering, and other household uses. Additionally, radon can enter the indoor air of a home via migration through cracks in foundations, through sumps and other subsurface utility fittings in the home. Charcoal canister devises can be used for short term testing of radon, while alpha-track detectors can be used for long-term testing. The charcoal test method provides fast turnaround results, while the alpha-track detectors can provide accurate averages of radon concentrations in an area.[162]

4.2 Data Needs for Assessing Radiological and Other Impacts at AUMs

Much progress has been made in understanding the nature and extent of radiological and other impacts at AUMs. Information at 523 AUM mine claims has been compiled from Weston Site Screen Reports, the 2007 Atlas, and other Weston spreadsheets including information about, among other, the volume of waste rock, and the magnitude of radiological impacts, the number and status of adits, and the proximity of AUMs to residential structures. However, data needs remain including but not limited: (a) the duration and frequency of Navajo People exposure to AUM contamination, (b) additional testing of unregulated water sources, (c) radon from open adits, (d) areas of AUMs without radiological data because of steep grades as discussed in the subsections that follow, and (e) potential migration of uranium impacted dust from AUMs.

---

161 March 6, 2008. Particulate Matter Sampling and Correlations to Wind Tunnel Durst Samples from the Cave Hills Harding, Co., South Dakota. US Forest Service. Website: http://uranium.sdsmt.edu/Downloads/PM%20Results%20Final%2003-06-08.pdf

162 Navajo Nation Environmental Protection Agency Radon program: http://www.navajonationepa.org/radon.html

4.2.1 Duration and Frequency of Navajo People Exposures to AUM Contamination

There are a number of mechanisms and pathways by which people are exposed to radiologically impacted material from AUMs. Potentially exposed populations include sheep-grazers, hikers, hunters, campers, herb-gatherers, medicine men,[163] ceremonial users, horse-back riders, and individuals using all-terrain vehicles or drinking uranium impacted surface water or groundwater. The duration and frequencies of such exposures have not been fully quantified. For example, greater exposures may occur in summer sheep camps in mountainous areas such as the Lukachukai Mountains.[164] The greatest exposures may potentially occur where human populations are proximate to AUMs (20 AUMs have a residential structure within 200-feet and 42 AUMs have gamma radiation levels above 2-times background, with a residential structure located within ¼-mile). More information is needed to quantify potential exposure frequency (the number of events per month or per year) and duration (the length of exposure time per event). This may help better quantify potential human health risks from such exposures.

Results of several health studies were recently summarized in the Second Five-Year report.[165] The Second-Year Report[166] also provided goals for additional health studies over the next five years including:

- Provisions for community bases services;
- Provisions of Radiation Exposure Screening and Education Program services;
- Collaboration with the Navajo Nation Division of Health Epidemiology Program; and
- On-going work by the Centers for Disease Control and Agency for Toxic Substances and Disease Registry on the Navajo Birth Cohort Study.

---

163 deLemos et al., Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. Environmental Health, July 2009.

164 deLemos et al., Development of risk maps to minimize uranium exposures in the Navajo Church Rock mining district. Environmental Health, July 2009.

165 USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, “Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation,” 2014.

166 USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, “Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation,” 2014.

4.2.2 Additional Testing of Unregulated Drinking Water Sources

There are 352 AUMs located within 1,320-feet of a drinking well and 592 AUMs located within one-mile of a perennial or intermittent surface water source.[167] The USEPA, NNEPA, Indian Health Service (HIS), Navajo Department of Water Resource (NDWR) and the Center for Disease Control (CDC) tested 240 unregulated water sources for uranium contamination, 29 of which exceeded drinking water standards for uranium or radionuclides (The Navajo Nation Primary Drinking Water Regulations Maximum Contaminant Level, NNPRDWR MCL, for uranium is 30 µg/L, and the gross alpha particle activity MCP is 15 pCi/L, including radium-226 but excluding radon and uranium;[168] see **Appendix A**[169]). Regulated water sources were not sampled because these sources are monitored and regulated in accordance with the Safe Drinking Water Act (SDWA). Based on this study, three wells were shut down and warning signs were posted at water sources that exceeded drinking water standards for uranium and radionuclides.

A 2010 USEPA report presented results in which 31 AUMs were evaluated where uranium ore deposits occurred below the water table, to assess potential uranium migration to groundwater. The study concluded that "mines with <u>elevated</u> potential of releasing uranium to groundwater and to unregulated wells near mines may have combinations of several factors, which may include but are not limited to:

- Uranium concentrations greater than the MCL in groundwater samples collected from downgradient wells;[170]
- Depth to water sources in relation to depth to ore deposits;
- Higher than average radiation at the surface;
- Potentially sizeable mass of uranium ore remaining at the mine;
- Extensive un-reclaimed waste piles;

[167] Tables 4 through 9 of the 2007 Atlas indicate a total surface water score of 160 for every AUM evaluated.
[168] April 2010, USEPA. Groundwater Pathway Assessment Report: Uranium Migration in the Navajo Nation and Shallow Water Sources (Eastern and North Central Region Mines).
[169] January 2013 Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation-five Year Plan Summary Report.
[170] Note that other criteria also may need to be evaluated when comparing groundwater concentrations between groundwater monitoring wells. Specifically, aquifer flow direction and well construction may need to be considered before concluding that water quality in monitoring wells is or is not reflective of potential mine contamination.

- Hydrologic conditions, such as rainfall, infiltration, aquifer sensitivity, and permeability, conducive to accelerated uranium migration; and/or

- Residence, schools or daycare centers within 200 feet of contamination associated with the mine."[171]

The study also concluded that mines with limited potential to release uranium to groundwater near mines having factors including but not limited to:

- Uranium concentrations less than the MCL in groundwater samples collected from downgradient wells;

- Shallow depth to water relative to depth to ore deposits;

- Moderate to low aerial radiation at the surface;

- Limited uranium ore remaining at the mine;

- Limited or no un-reclaimed waste piles;

- Hydrologic conditions such as rainfall, infiltration, aquifer sensitivity, and permeability, unfavorable to extensive uranium migration; and

- No residences, schools, or daycare centers within 200 feet of contamination associated with the mine.[172]

In addition, the study concluded that mines with an undefined potential of releasing uranium to groundwater sources in the vicinity of mines had (a) insufficient analytical results, were located where aerial radiation with radiation greater than background levels at the surface, and were adjacent to possibly high or unknown mass of uranium ore remaining at the mine.[173]

---

171 April 2010, USEPA. Groundwater Pathway Assessment Report: Uranium Migration in the Navajo Nation and Shallow Water Sources (Eastern and North Central Region Mines).

172 April 2010, USEPA. Groundwater Pathway Assessment Report: Uranium Migration in the Navajo Nation and Shallow Water Sources (Eastern and North Central Region Mines).

173 April 2010, USEPA. Groundwater Pathway Assessment Report: Uranium Migration in the Navajo Nation and Shallow Water Sources (Eastern and North Central Region Mines).

In 2008, the Centers for Disease Control and Prevention, USEPA, NNEPA and the Diné Network for Environmental Health identified 29 unregulated water sources with levels of uranium and other radionuclides in excess of USEPA drinking water standards. The Indian Health Service is currently working to complete the design and construction of four projects funded at the conclusion of the original Five-Year Plan. Further, the Navajo Nation Department of Water Resources is continuing to implement water hauling with deliveries occurring in the Western Agency, Eastern Agency, Chinle Agency, and Fort Defiance Agency. According to the Second Five-Year Plan, has established a goal to increase access to safe drinking water in expanded geographic areas and to continue to implement water hauling programs.[174]

Although much has been learned about groundwater and surface water contamination within the Navajo Nation, additional data are needed to understand the typical range of radiological concentrations occurring in the absence of historic mining ("background" concentrations) to further understand, identify and address those water resources impacted by AUMs.[175]

4.2.3 Radon from Open Adits

Radon (^{222}Rn) is emitted from uranium mine ventilations shaft exhaust and is therefore another major source of environmental contamination within the Navajo Nation. Data is needed to (a) quantify radon emissions from open adits under varying meteorological conditions (b) assess potential human exposures to such radon emissions and (c) quantify associated risks from such exposures.

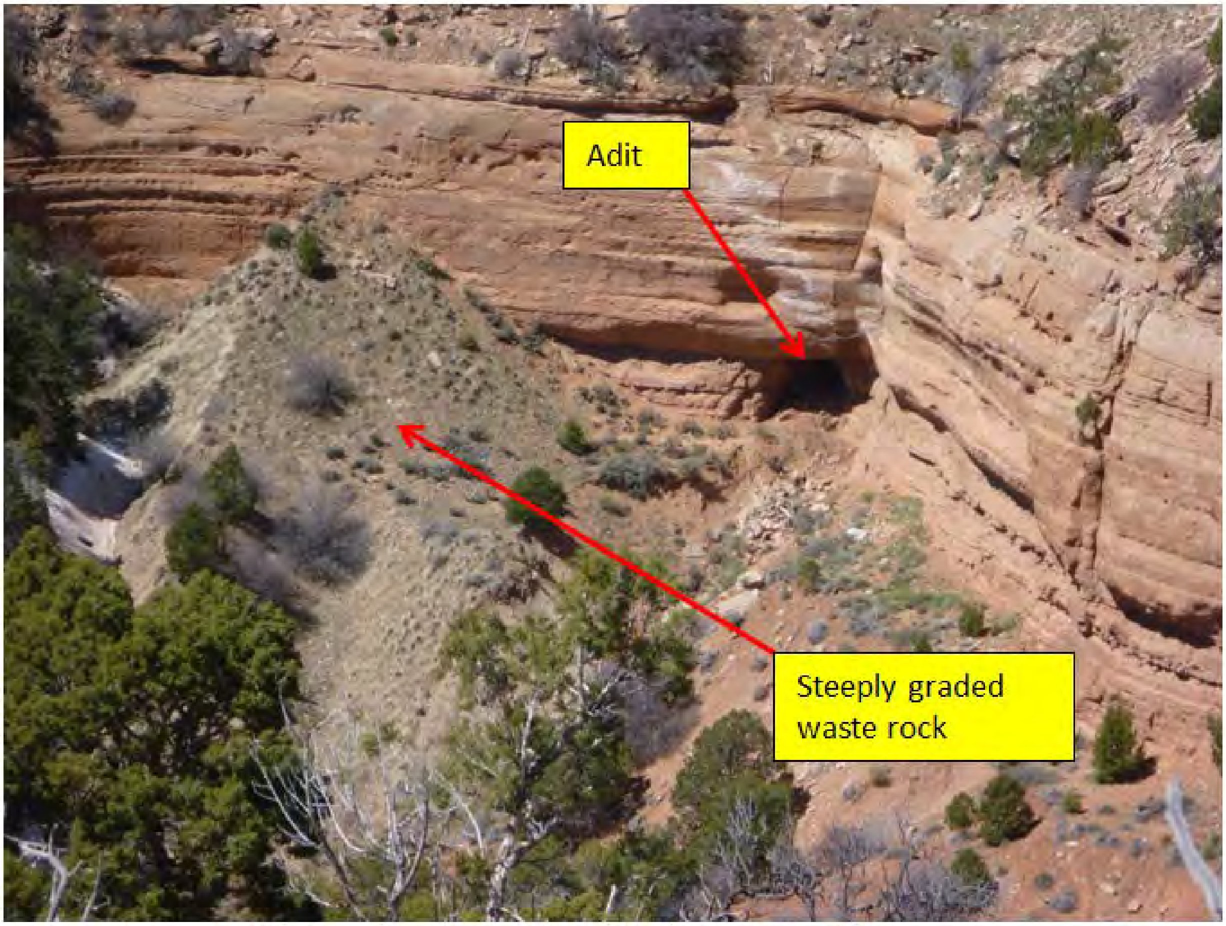
4.2.4 Areas of AUMs without Radiological Data Because of Steep Grades

During investigations conducted by Weston, gamma radiation measurements were unable to be collected at certain locations due to steep grades. Such conditions precluded using the GPS-based survey equipment (either all-terrain vehicles or walking carrying equipment in backpacks). Other gamma radiation measurement techniques are therefore needed to access such areas so that radiation levels at such locations can be quantified to assist in evaluating and selecting cleanup alternatives.

---

[174] USEPA, BIA, NRC, DOE, HIS and ATSDR in consultation with the Navajo Nation, Second Five-Year Plan, "Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation," 2014.

[175] Note that additional testing of unregulated water sources may not yield appropriate data as little may be known about the construction of unregulated wells including the depth of the screened interval.



Waste rock adjacent to Adit in Lukachukai Mountains

4.2.5 Potential Migration of Uranium Impacted Dust from AUMs

There are little to no data assessing the content of radiological materials in wind-blow dust originating from AUMs. Such measurements are of particular importance in populated areas adjacent to AUMs where such dust could be inhaled by residents. Windblown dust from AUMs can also settle on food crops, resulting in direct ingestion of metals and radionuclides in dust from the mining areas. For example, there is an abandoned open-pit uranium mine located on Flint Butte (also referred to as "Flat Top Mountain"[176] and "Flat Top Mesa"[177]) just northeast of the hamlet of Ludlow in Harding County, South Dakota[178] (see images that

---

[176] Groth, F.A., *Memorandum to R.T. Zitting re: Stenseth Properties: McCurdie Lease and Flat Top Mountain; Sec. 27 & 28, T22N, R6E, Harding Co., South Dakota*, September 19, 1961, submitted as part of Tronox's August 31, 2009 response to USEPA Region 8's request for information re: Flat Top Mine near Ludlow, South Dakota.

[177] Holden, K.A., *Annual Production Geology Report for the Year 1964, Uraniferous Lignite Project, Bowman, North Dakota*, undated, submitted as part of Tronox's August 31, 2009 response to USEPA Region 8's request for information re: Flat Top Mine near Ludlow, South Dakota.

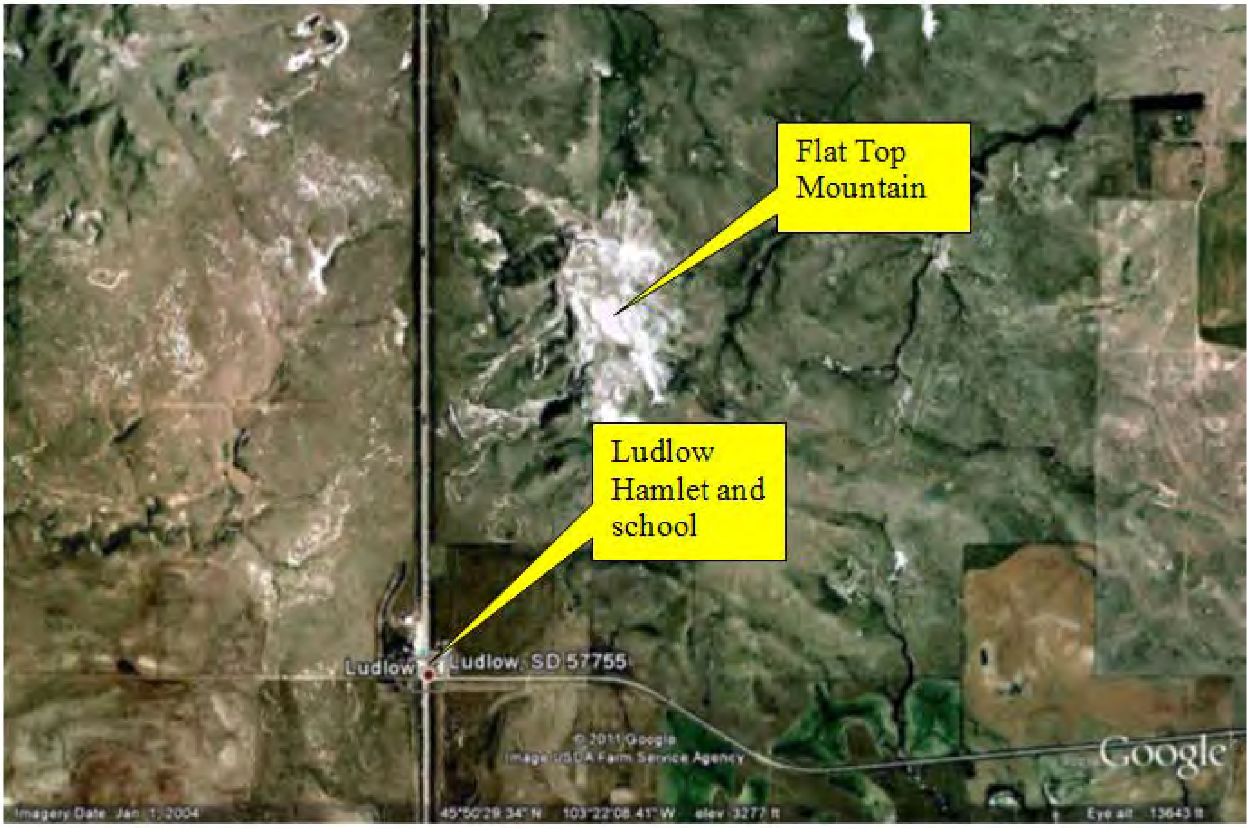
[178] Stone, J.P., et al., *Final Report: North Cave Hills Abandoned Uranium Mines Impact Investigation;* April 18, 2007.

follow showing proximity of the AUM to Ludlow). While this AUM is not within Navajo Nation, it provides a good example of the need to monitor wind-blow dust originating from the AUM. Surface gamma readings at the mine ranging from 22 to 140 μR/hour have been recorded. (These levels are up to an order of magnitude greater than local background gamma levels [12-14 μR/hour].[179]) No other environmental sampling has been conducted, although the Flat Top AUM although it has been identified as a potential source of molybdenosis (molybdenum poisoning) in cattle grazing at and in the vicinity of the Site.[180] Uranium and other metals have been detected at concentrations in excess of background levels in surface water and sediment samples collected in a drainage originating at the AUM.[181] Although the Ludlow school is located proximate to the AUM, there are no data indicating whether or not dust migrating from the AUM is radiologically impacted and whether or not the nearby residential population is being exposed to unacceptable concentrations of this material.

179 U.S. Department of Agriculture, Forest Service – Region 1, June 2005. "Draft Final Engineering Evaluation/Cost Analysis (EE/CA), Riley Pass Uranium Mines, Harding County, South Dakota."

180 Stone, L.R., et al., *Molybdenosis in an area underlain by uranium-bearing lignites in the northern Great Plains*, Journal of Range Management, 1983, as cited in Stone, J. et al., *Final Report: North Cave Hills, Abandoned Uranium Mines Impact Investigation*, April 18, 2007.

181 Stone, J. et al., *Final Report: North Cave Hills, Abandoned Uranium Mines Impact Investigation*, April 18, 2007.



Aerial view of Site (note proximity of Site to the hamlet of Ludlow)

View of the Site from Ludlow

View of Ludlow from the Site

5.0 CLEANUP OF URANIUM CONTAMINATION PERFORMED TO DATE IN OR NEAR THE NAVAJO NATION

Roux Associates reviewed publicly available resources/documents and other information provided by USEPA and Navajo Nation personnel to develop an understanding of the degree, scope, status, and success of cleanup performed to date at AUMs and other uranium-related sites located both within and outside the Navajo Nation. To begin with, Roux Associates visited the following topical websites to obtain general programmatic information related to AUMs and other uranium-related sites within the Navajo Nation, as well as links to more specific information regarding individual sites:

- USEPA Region 9 - Addressing Uranium Contamination on the Navajo Nation http://www.epa.gov/region9/superfund/navajo-nation/

- USDOE, Office of Legacy Management-Legacy Management Sites http://energy.gov/lm/office-legacy-management

Using the links to individual sites found at the above websites, Roux Associates obtained fact sheets, annual inspection reports, action memoranda, removal action completion reports, and USEPA Pollution/Situation Reports ("Polreps"), many of which yielded valuable information for this Initial White Paper. Roux Associates also contacted several USEPA On-Scene Coordinators (OSCs) to solicit additional information about their sites, including updates to the information available on the individual sites' web pages and any "lessons learned" that could be included in this Initial White Paper.

Based on review of the information obtained per the above, it became apparent to Roux Associates that, although a fair amount of assessment work has been conducted at AUMs[182] within the Navajo Nation, only limited cleanup has been performed to date for AUMs, thereby limiting the amount of information-particularly lessons learned-that can be applied to this Initial White Paper. For the most part, cleanup at AUMs within the Navajo Nation has only involved interim (temporary) cleanup actions of varying scale and complexity performed under CERCLA. And although major cleanup actions have been performed at four former uranium-processing mills within the Navajo Nation under UMTRCA, those actions too yielded only limited information relevant to this Initial White Paper (in that the

[182] In this Initial White Paper, the term "AUMs" comprises both mines and mining-related sites, such as ore transfer stations.

approaches used for addressing uranium-contaminated materials at those sites were generally the same). Therefore, to augment the amount of information available for use in this Initial White Paper, Roux Associates also reviewed documentation for CERCLA and UMTRCA cleanup actions performed at AUMs and other uranium-related sites located outside the Navajo Nation. This additional review extended only to sites in the vicinity of the Navajo Nation, where the physical and climatic settings may be similar to sites located within the Navajo Nation.[183]

To begin the expanded review process, Roux Associates further explored the aforementioned USDOE website and reviewed the following additional topical websites:

- USEPA Region 6 – Grants Mining District, New Mexico http://www.epa.gov/region6/6sf/newmexico/grants/nm_grants_index.html

- USEPA Superfund – Superfund Sites Where You Live http://www.epa.gov/superfund/sites/

As was done for the sites within the Navajo Nation, Roux Associates used the links to individual sites found at the above websites to find additional information relevant to this Initial White Paper. Roux Associates also contacted a U.S. Forest Service OSC to solicit information about a cleanup action performed at an AUM on federal land.

The information gathered by Roux Associates regarding cleanup performed to date at AUMs and other uranium-related sites within and in the vicinity of the Navajo Nation is presented in **Table 1**. This table lists the various sites researched by Roux Associates and, for each site, provides site contact information (if determined), status of cleanup actions, highlights of the cleanup performed for soil/waste rock, cap details (if capping was part of the cleanup),[184] cost information (where available), and lessons learned/other notes. The subsections below provide more detailed information regarding the various cleanup actions completed to date at AUMs and other uranium-related sites within and near the Navajo Nation.

---

183 There are many additional AUMs located further away from the Navajo Nation, several of which are Superfund sites. These were not reviewed because their physical and climatic settings likely differ enough to render them only somewhat applicable to this Initial White Paper.

184 Liner details are also provided for the two sites where liners were part of the cleanup.

5.1 Overview of Uranium Cleanup Performed To Date Within the Navajo Nation

Based on Roux Associates' review of available information, large-scale cleanup performed to date at AUMs and other uranium-related sites within the Navajo Nation is limited to (1) CERCLA cleanup actions at five AUMs, (2) UMTRCA cleanup actions at five former uranium mills, and (3) one Navajo Nation/USDOE cleanup action at a mill-related site. Each category of cleanup action is discussed separately below.

5.1.1 CERCLA Cleanup Actions at AUMs

Large-scale CERCLA cleanup actions have been performed at five AUMs within the Navajo Nation:

1. Northeast Church Rock (NECR) Mine
2. Quivira Church Rock #1 Mine
3. Skyline Mine
4. Cove Transfer Station Sites
5. Section 32 Mine

These cleanup actions are all considered interim actions and generally consisted of the removal of uranium-contaminated soil and waste rock from areas with a high potential for exposure and/or migration followed by consolidation of the excavated material in more secure areas and/or within interim repositories.

<u>NECR Mine</u>

The NECR Mine is located in the Pinedale Chapter. A total of approximately 136,000 cubic yards (cy) of contaminated soil was removed during a series of cleanup actions performed between 2007 and 2012 in a residential area immediately adjacent to the mine and in two adjacent surface water drainages/drainage areas (all located in the Coyote Canyon Chapter). Some of the soil (~6,000 cy) was disposed offsite at a permitted facility in Grandview, Idaho; the remainder was placed atop the existing 900,000-cy mine waste pile at the NECR Mine site itself, which was re-graded and subsequently covered with 6 to 12 inches of clean soil (top 6 inches, slopes 12 inches) pending final removal of the mine waste pile offsite at a later date.[185]

Cleanup Action in Residential Area Adjacent to NECR Mine

185 The soil sent off-site for disposal was removed during the initial cleanup actions, which were performed by USEPA; the remainder of the contaminated soil was removed by the owner of the mine (United Nuclear Corporation [UNC]), which performed the subsequent cleanup actions. Final cleanup of the mine waste pile is pending Nuclear Regulatory Commission (NRC) approval of USEPA's plan to dispose of the waste at the nearby former UNC Church Rock mill site (see **Section 5.1.2**).

Re-graded and Covered Mine Waste Pile at NECR Mine (2010)

<u>Quivira Church Rock #1 Mine</u>

At the Quivira Church Rock #1 Mine, located in the Coyote Canyon Chapter just across a small valley from the NECR mine (with the aforementioned residential and drainage areas in between), two cleanup actions have been performed. The first, performed in 2010, included the following, among other measures:

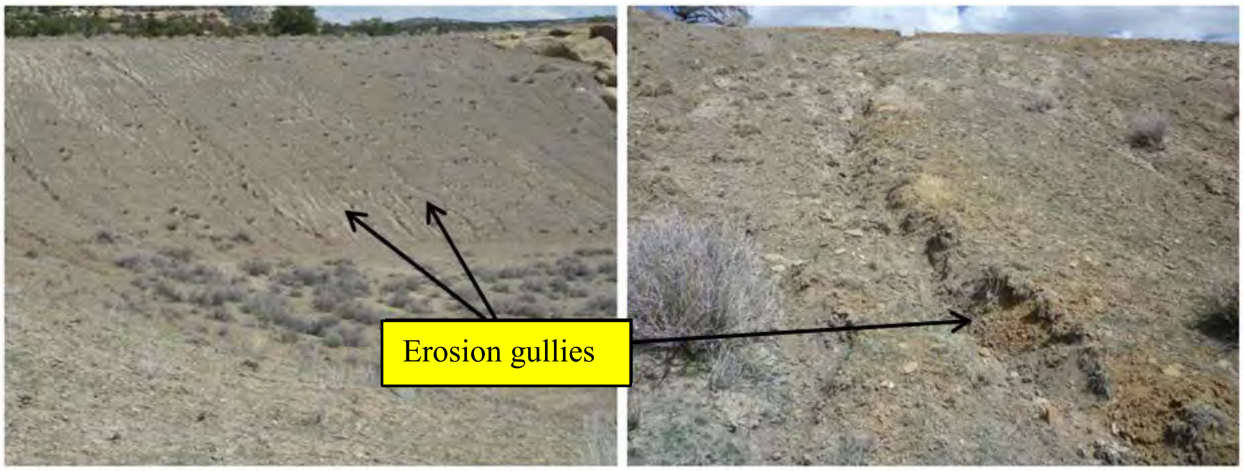
- Partial regrading of the existing mine waste pile at Church Rock #1, which although reclaimed in the past had since become deeply eroded;

- Implementing near-term sediment and erosion controls (including spraying the slopes of the mine waste pile with a mulch/tackifier mixture) to prevent continued discharge of contaminated or potentially contaminated materials to an adjacent arroyo and other offsite areas;

- Chip sealing (paving) of a portion of Red Water Pond Road (a local access road that was formerly used as a haul road for trucks leaving Church Rock #1 with uranium ore) and spraying of tackifier (soil stabilizer) to the adjacent shoulders; and

- Applying soil stabilizer to the Church Rock #1 access road and the portion of Red Water Pond Road nearest the mine.[186]

The following photographs of the Church Rock #1 waste pile, taken in 2010, show the erosion of the soil cap placed on the mine waste pile as part of reclamation activities performed at the site in the early 1990s.



Erosion of reclaimed waste pile at Church Rock I (April, 2010)

Close-up of erosion gully on reclaimed waste pile at Church Rock I (April, 2010)

The photograph below shows the re-graded western slope of the mine waste pile at Church Rock #1 and some of the near-term sediment and erosion control measures implemented pursuant to the first cleanup action at the site.

[186] These areas were not chip-sealed as originally planned due to concerns over the structural integrity of the existing Red Water Pond Road Bridge that spans the arroyo adjacent to the mine (no heavy equipment was permitted to cross the bridge).

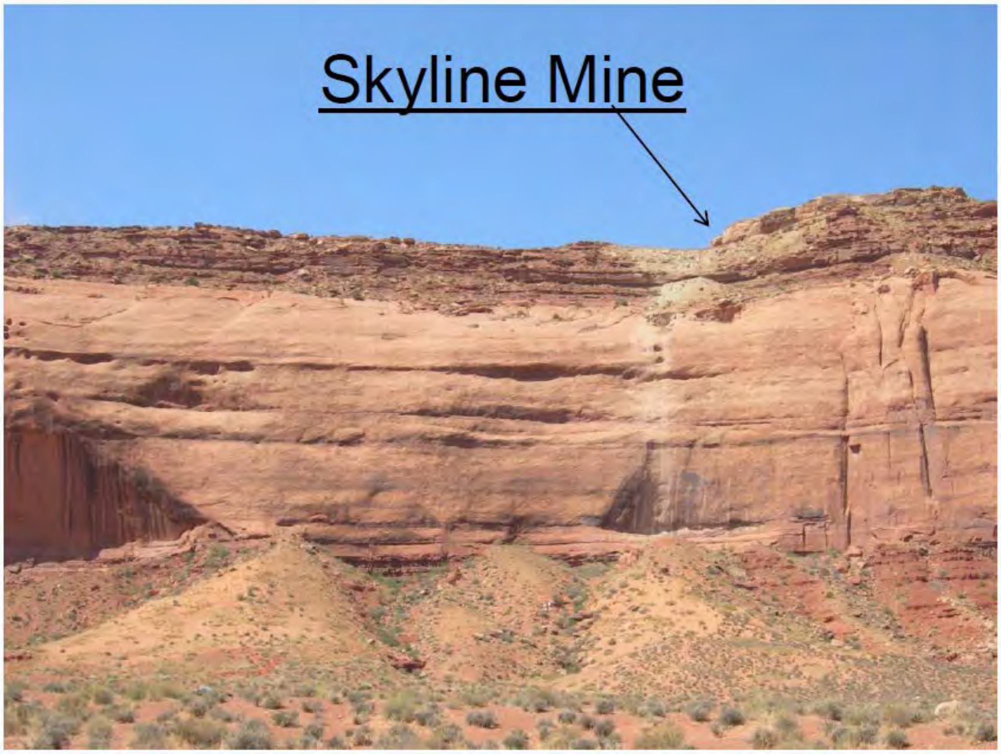
Subsequent to the first cleanup action and based on a Removal Site Evaluation performed as part thereof, approximately 17,000 cy of contaminated soil beneath and adjacent to the stretch of Red Water Pond Road that had previously been chip-sealed were excavated as part of a second cleanup action (performed in 2012). The excavated material was transported to the Church Rock #1 mine site for interim storage atop the existing mine waste pile until final cleanup of the site is performed. The relocated material was covered with 6 inches of clean soil which was seeded for revegetation. The excavated road and shoulder areas were also reconstructed and the shoulder areas seeded for revegetation.

<u>Skyline Mine</u>

At the Skyline Mine, located in the Oljato Chapter, approximately 25,000 cy of mine waste was removed from several areas at and in the vicinity of the mine and consolidated within a lined and capped repository. There were many logistical challenges associated with this cleanup action (performed in 2011), not least of which was the fact that the location selected for the repository was atop the mesa on which the mine was located-700 feet above where the majority of the mine waste was situated.[187] This required improvement of the existing

[187] The Skyline Mine itself was located atop the mesa, but mine waste had been pushed over or fell off the top of the mesa to cover the talus slopes on the valley floor below.

access road to the top of the mesa to allow for movement of heavy equipment. It also required the use of a cable yarder to haul the waste to the top of the mesa.



Location of Skyline Mine and Contaminated Talus Slopes on Valley Floor

Access Road to Top of Mesa

Loading of Cable Yarder on Valley Floor

Use of Cable Yarder to Transport Mine Waste to Repository at Top of Mesa

The Skyline repository, which is partly below-ground, is lined with a high density polyethylene (HDPE) geomembrane and covered with a second HDPE geomembrane, as well as a rock "bio-barrier"[188] and soil cap to protect the geomembrane from burrowing animals and sunlight, respectively. The two HDPE membranes are fused together along the edges of the repository to totally encapsulate the waste, while the soil cap, in addition to protecting the HDPE cover from sunlight, also serves as a radiation barrier, attenuating gamma emissions from the encapsulated waste to an acceptable level. Further, as an added measure of protection, the repository was also strategically located near a surface divide (to limit storm water run-on) and on a sloping surface (to help shed storm water runoff).

Skyline Mine Repository Construction – Bottom Liner

[188] A bio-barrier is layer of rock designed to prevent "biointrusion," i.e., animal (e.g., prairie dog) burrowing, beyond a certain depth.

Skyline Mine Repository Construction – Soil Cap and Drainage Diversion Channel

The repository cap was seeded with native grasses following completion of construction activities,[189] as were all areas disturbed by the cleanup action. However, the low organic content of the cover soil prevented much growth of vegetation on the repository. As a result, in the years following completion of the cleanup action at the Skyline Mine, some erosion of the soil cover has occurred, as shown in the photographs below (taken in 2014).

[189] Native seed mix was applied to the cap to improve the aesthetic appearance of the cap, to help stabilize the upper soil layer, and to produce fodder for grazing; although grasses typically promote transpiration of any precipitation infiltrating the soil layer, the cap was not designed as an evapotranspiration (ET) cap.

Erosion at Skyline Mine – Northwest Side of Repository

Erosion at Skyline Mine – Southwest Side of Repository

Cove Transfer Station

At the Cove Transfer Station Sites, two sites (Transfer Station 1 [TS1] and Transfer Station 2 [TS2]) in the Cove Chapter that were formerly used for stockpiling of uranium ore from mines in the nearby Lukachukai Mountains, approximately 13,700 cy of contaminated soil and mine waste rock was excavated (mostly from TS1) and consolidated in a contaminated soil stockpile constructed at TS2 during a cleanup action performed in 2012 and 2013. The stockpile, which occupies approximately 97,000 square feet and is 3 to 4 feet high with 25% side slopes, was not capped but was only graded, treated with soil stabilizer (for erosion control and dust suppression), and fenced. According to the Removal Action Report, "*the stabilizer will likely degrade within one to two years after application given the region's seasonal weather extremes, and will likely lose the ability to limit erosion and fugitive dust emissions in the future*." Excavated areas "*that presented elevated gamma activity concentrations following removal activity*" were capped with approximately 12 inches of clean soil from a local borrow source. One year later, improvements of the protective cap were implemented to address erosion of the cap.

TS1 – Clean Backfill at Former Cove Transfer Station Along Western Slope Adjacent to Route 33

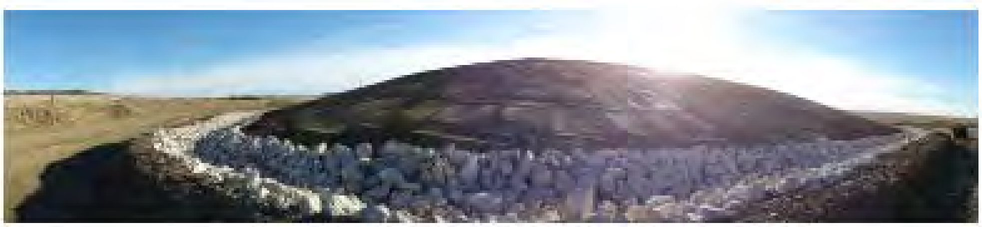
TS1 – Clean Backfill East of Residential Structure Adjacent to Former Cover Transfer Station

TS2 – Final Stockpile Slope (East Side) at Former Cove Transfer Station

<u>Section 32 Mine</u>

A cleanup action similar to that completed at the Cove Transfer stations was performed at the Section 32 Mine (Casamero Lake Chapter) in 2012, during which approximately 30,000 cy of contaminated soil and mine waste was excavated from portions of the former mine area and from an associated transfer area nearby and consolidated in a temporary stockpile constructed in the former mine area. The stockpile was shaped and compacted, and "at least two layers" of soil tackifier (stabilizer) were applied. A storm water catch basin was installed around the stockpile, with a sediment basin added which "*collects water from the catch basin and settles out any loose sediments*". The stockpile area was also fenced.

Mining Waste at Section 32 Mine



180-Degree View of Stockpile (November 2012) at Section 32 Mine

Applying Second Coat of Tackifier to Stockpile (November 2012) at Section 32 Mine

Inspection of the site after ten months revealed some erosion of the stockpile surface and siltation of the surrounding drainage channels, as shown in the image below.

Erosion and Siltation at Section 32 Mine One Year Later (September 2013)

To address this situation, contractors remobilized to the site the following spring to install coir fabric[190] on the stockpile. The storm water drainage system was also "*completely reconstructed to better handle the monsoon rains*" and help anchor the coir fabric. Together, these measures appear to have significantly reduced erosion of the stockpile surface.

Areas disturbed during the cleanup action were also re-seeded with native vegetation in 2014.

Coir Fabric on Stockpile and Reconstructed Drainage Channel at Section 32 Mine (April 2014)

[190] Coir fabric is a strong and long-lasting erosion control material made from a natural and biodegradable coconut fiber. It is used to increase soil stabilization, decrease erosion, and allow vegetation to take root.

Stockpile in Fall 2014 at Section 32 Mine (Post-monsoon)

5.1.2 UMTRCA Cleanup Actions

The UMTRCA cleanup actions performed within the Navajo Nation (during the 1980s and 1990s) were much more extensive than the cleanup actions described above, as they involved the decommissioning and demolition of large facilities, management of much larger volumes of radioactive mill tailings and associated waste (millions of cubic yards), and cleanups to address contaminated groundwater.[191] At four of the five UMTRCA sites within the Navajo Nation (Shiprock Disposal Site, Tuba City Disposal Site, Mexican Hat Disposal Site, and the former UNC Church Rock mill site), tailings and associated contaminated materials (including debris from demolished mill buildings and windblown tailings from offsite vicinity properties) were consolidated into an unlined disposal cell built on-site atop some of the existing tailings.[192] The disposal cells at the three UMTRCA Title I sites (Shiprock, Tuba City, and Mexican Hat)[193] range in size from 50 to 77 acres and rise up to 50 feet above

---

191 Groundwater cleanup programs are ongoing at several of the UMTRCA sites, but the discussion of these programs is beyond the scope of this Initial White Paper.

192 At the fifth site (Monument Valley Processing Site), mill tailings were removed and transported to the Mexican Hat Disposal Site, located ten miles away.

193 UMTRCA Title I sites were former uranium processing mills that were inactive at the time UMTRCA was enacted. Uranium processing facilities that were still active at the time UMTRCA was enacted are known as Title II sites; cleanup of these facilities was deferred until closure of the facility. The former UNC Church Rock mill site is a Title II site.

the surrounding area. They were all built with multi-component caps comprising (1) a low-permeability radon barrier (the first layer over the contaminated materials) consisting of clayey or compacted sandy silty soils, (2) a layer of granular bedding material (which acts as a capillary barrier), and (3) a rock (riprap) erosion-protection layer. The cap specifications for each site are shown below.

	Shiprock	Tuba City	Mexican Hat
Radon Barrier	76 inches	44 inches	24 inches
Bedding Layer	6 inches	6 inches	6 inches
Riprap (top)	12 inches	12 inches	12 inches
Riprap (sides)	12 inches	6 inches	8 inches
Top slope	2 to 4 percent	3 to 4 percent	2 percent
Side slope	20 percent	20 percent	20 percent

Rock-lined aprons and drainage ditches were constructed upslope and/or around the disposal cells to divert surface runoff around and away from the cells. The two photographs that follow show different views of the Mexican Hat disposal cell, which is typical of the disposal cells built at the UMTRCA Title I sites.

Mexican Hat UMTRCA Disposal Cell (in background)

Close-up View of Disposal Mexican Hat Cell Cap and Drainage Channel

Annual inspection reports prepared by USDOE for the three UMTRCA disposal cells located within the Navajo Nation do not indicate that any significant problems with erosion, settlement, slumping, animal intrusion, or other issues that could adversely affect the effectiveness of the disposal cells have been experienced. The most common problem reported is accumulation of windblown sand in rock surfaces (see photograph below), which can facilitate growth of undesirable vegetation. Periodic application of herbicides has been required at some sites to control deep-rooted vegetation on the cell cover.

TUB 4/2014. PL-10. Windblown sand in diversion channel.

Tuba City

At the former UNC Church Rock mill site (Title II), the tailings piles were reclaimed and covered following closure of the mill in 1982. Windblown tailings were excavated and disposed in the tailings piles, and the tailings were regraded so that there was a minimum 7-foot thickness of coarse-grained tailings over the fine-grained tailings (which have higher radium concentrations and produce greater radon emissions compared to the coarse-grained tailings). Most of the tailings were then capped with an interim cover consisting of 12 inches of compacted soil followed by a final cover comprising an additional 6 inches of compacted soil and a 6-inch soil/rock matrix later for erosion protection.[194] Drainage swales were constructed on and around the reclaimed tailings piles. A portion of the tailings pile was left uncovered as it was (and still is) being used as an evaporation pond for groundwater pumped from underlying aquifers as part of the site's groundwater cleanup. The evaporation ponds may be reclaimed after groundwater cleanup is complete and the ponds are no longer needed (and after waste from the NECR Mine is relocated to the UNC site, if approved by NRC).

[194] The USEPA report (Fourth Five-Year Review Report) from which these cap specifications were obtained states elsewhere in the report that the tailings disposal cell caps comprise 18 to 24 inches of compacted soil overlain by 3 inches of rock mulch, with a "final layer" consisting of an unspecified amount of compacted soil.

5.1.3 Navajo Nation/USDOE Cleanup Action

The Navajo Nation, in cooperation with the USDOE, performed a cleanup action at the Tuba City Highway 160 Site, located opposite the aforementioned Tuba City Disposal Site. The Highway 160 Site comprises approximately 16 acres of grazing land found to be impacted with residual radioactive material (RRM) from the former Tuba City mill site. Approximately 6,000 cy of RRM was excavated and disposed offsite at the Grand Junction (Colorado) Disposal Site, an UMTRCA site authorized to accept RRM from cleanup of non-mill properties such as the Highway 160 Site.

5.2 Overview of Uranium Cleanup Performed To Date Outside the Navajo Nation

One AUM and ten uranium-related sites were identified in the vicinity of the Navajo Nation at which cleanup actions have been performed under CERCLA or UMTRCA. Each category of sites is discussed separately below.

5.2.1 CERCLA Cleanup Actions

A CERCLA cleanup action was performed at the San Mateo Mine, an AUM located in the nearby Grants Mining District, and CERCLA cleanup actions have been performed at three uranium-related Superfund sites near the Navajo Nation. The latter were all former uranium mills not decommissioned as part of the UMTRCA Title I-based Uranium Mill Tailings Remedial Action (UMTRA) program because they were still active at the time UMTRCA was enacted or, in one case, operated as a federal facility. These sites are discussed below.

San Mateo Mine

The U.S. Forest Service performed a CERCLA cleanup action at the San Mateo Mine, located in Cibola County, New Mexico (within the Cibola National Forest) in 2012 and 2013. During this cleanup action, approximately 136,300 cy of contaminated mine waste rock was excavated from both on-site and off-site areas and consolidated on-site within the footprint of the main waste rock pile. The consolidated waste was graded and capped with an evapotranspiration (ET) cap, while the excavated areas were regraded and reseeded. Unlike the caps at the UMTRCA sites, which are designed to shed storm water runoff as quickly as possible, an ET cap stores storm water until it is evaporated or transpired by plants that become established on the cap. The ET cap at the San Mateo Mine comprised a 12-inch clay loam layer (first layer above the waste), overlain in turn by a 12-inch sandy loam layer and an 18-inch admixture layer (rock blended with sandy loam). For this top layer, 2-inch rock was used on the flatter top of the disposal cell, while 3-inch rock was used on the side slopes (which were at a 20% slope). Upon completion of the cap, it was seeded with native grass (using a seed drill on the majority of the site and hydro-seeding methods on the steeper slopes). The completed disposal cell is shown in the image below.

San Mateo Mine Disposal Cell (foreground)

Rock-lined surface water diversion channels were also constructed around the disposal cell, which was also fenced to prevent entry by large animals and vehicles.

Subsequent monitoring inspection of the site in 2014 revealed minor erosion, including the development of several minor rills on the face of the disposal cell (see image below) and small gullies in two areas. These were addressed using riprap, straw bales, and coconut matting. Revegetation, which was initially slow due to drought, has progressed since. Some treatment with herbicide was required to eradicate some undesirable plants which had become established.

Minor Erosion on North Face of Repository in February 2014

San Mateo Mine

Revegetation in May 2015

San Mateo Mine

Homestake Mining Company Superfund Site (Cibola County, New Mexico)

The Homestake Mining Company Superfund Site was named to the National Priorities List (NPL) in 1983. There are three operable units (OUs) at this site: OU1 involves cleanup of site groundwater impacted by seepage from the tailings piles; OU2 involves long-term stabilization of the tailing piles, as well as surface reclamation and site closure; and OU3 involves elevated radon concentrations in off-site residential neighborhoods. OU2 and OU3 are relevant to this Initial White Paper in that they both included cleanup actions to address exposure to contaminated soil, tailings, and mining-related waste. For OU2, windblown mill tailings/contaminated soil in the mill area were excavated and disposed within the tailing piles (the depth of excavation ranged up to 5 feet, with an average of 2 feet). The piles were then closed, recontoured, and covered with interim covers. A radon barrier and "*erosion-protection cover*" of unspecified design (but evidently built in part using tailings) were constructed on the sides of the larger of the two tailings piles at the site (containing an estimated 21 million tons of tailings), with an interim soil cover (also of unspecified design) on top. An interim soil cover was also constructed on the second, smaller tailings pile (containing an estimated 1.2 million tons of tailings). The interim soil covers will be replaced with final radon barriers once groundwater restoration at the site has been completed.

OU3 involved the installation of radon mitigation systems to address elevated radon concentrations in the indoor air of a number of residences located in subdivisions adjacent to the former mill site. USEPA concluded that the elevated radon in the subdivision was not attributable to past mill operations but rather to past mining activity in the area. A CERCLA Removal Action was therefore performed to remove approximately 1,000 cy of "identified radiological soil/debris" from the affected properties (now collectively referred to as the "Mormon Farms Site"). The excavated material was temporarily stored in a nearby staging area and then disposed offsite. Excavated soils were replaced with clean fill.

Uravan Uranium Project Superfund Site (Montrose County, Colorado)

The Uravan Uranium Project Superfund Site was named to the NPL in 1986. Cleanup actions performed at this site that are relevant to this Initial White Paper include the capping and revegetating of nearly 10 million cubic yards of radioactive tailings, excavation and consolidation of 530,000 cubic yards of raffinate crystals in secure areas onsite, securing 12 million cubic yards of tailings waste along the San Miguel River, the excavation and on-site disposal (in the tailings piles) of contaminated soil, and the replanting of excavated areas. Tailings piles were capped with a low-permeability radon barrier of unspecified construction (first layer over the tailings), overlain by a frost-protection layer composed of compacted soil, a granular bedding layer, and a riprap erosion protection layer. Raffinate crystals were relocated to a former quarry pit, encapsulated in clay-lined cells, and capped with an earthen cover topped by riprap.

<u>Monticello Mill Tailings Superfund Site, San Juan County, Utah</u>

The Monticello Mill Tailings Superfund Site is the former location of a USDOE uranium- and vanadium-processing facility named to the NPL in 1989. Cleanup actions performed at this site that are relevant to this Initial White Paper include the excavation of over two million cubic yards of contaminated soil and sediment, windblown tailings, and tailings piles and consolidation of the excavated material in a repository built at a nearby USDOE-owned property (about one mile from the former mill site). Excavation extended below the water table over a large area of the mill site; this necessitated the construction of various drainage controls and groundwater interception trenches and the rerouting of a perennial stream. Over 50 million gallons of groundwater pumped from the excavations was treated onsite in a temporary treatment system prior to discharge to the aforementioned stream.

The repository was designed to meet protective standards specified in 40 CFR 192.02 (USEPA standards for the control of RRM) but was also designed to be functionally equivalent to a Resource Recovery and Conservation Act (RCRA) Subtitle C hazardous waste landfill on account of the variety of other-than-radioactive contaminants disposed, including asbestos, petroleum products, and laboratory wastes. The design features that made the repository functionally equivalent to a RCRA Subtitle C landfill include a lined, multi-layered cover system and a double-lined base. The cover system comprises a compacted soil radon barrier, a 60-mil-thick HDPE geomembrane moisture barrier, and a vegetated ET soil layer on the surface. The ET layer consists of a 5.5-foot-thick layer of fine-textured soil overlying a 12-inch-thick sand-and-gravel layer. The upper 8 inches of the cap is a gravel admixture designed to control erosion and function as a mulch, and a layer of cobble-sized rock located about a foot from the bottom of the fine-textured soil acts as a bio-barrier.

The double-lined base of the repository consist of two composite liners, each comprising a 60-mil-thick HDPE geomembrane overlying a geosynthetic clay liner, with a leak detection system (geo-net drainage layer) in between. A leachate collection system, consisting of a 12-inch-thick sand layer drained by a network of perforated pipes, was also installed above the upper liner. Leachate from the repository ("*residual construction water applied while hauling and placing the wastes in the repository*") is pumped to a triple-lined solar evaporation pond ("Pond 4") with a storage capacity of 16 million gallons. To date, no leachate has been detected in the leak detection system (i.e., no leachate has penetrated the upper liner).

Photographs of the repository and Pond 4 taken during the 2011 annual inspection of the site are provided below.

11. Vegetated disposal cell cover, view to the west from center monument.

Monticello Mill Tailings Superfund Site

12. Vegetation on rock side slope of repository.

Monticello Mill Tailings Superfund Site

7. Pond 4 showing siltation, vegetation, and standing water.

Monticello Mill Tailings Superfund Site

Initially, repository vegetation performance criteria were not achieved, but more recently the vegetation community has been deemed "healthy." Several areas of the repository were treated with herbicide to control noxious weeds. Routine inspections of the repository "indicate no evidence to suspect compromise of the repository cover (slumping, settlement, erosion, biointrusion) in preventing precipitation infiltration and radon emission." A photograph of the cover vegetation taken during the 2014 annual site inspection follows.

Photo 17. Cover Vegetation, View East

Monticello Mill Tailings Superfund Site

A portion of the material disposed in the on-site repository was excavated from 34 properties on rural land surrounding and downstream of the mill site, which were contaminated by runoff and windblown dust from the mill, as well as from 424 contaminated properties in the residential and commercial area of Monticello. The latter, contaminated both by windblown dust from the mill site and by use of radioactive tailings as construction material, constitute the Monticello Radioactively Contaminated Properties Superfund Site, which is administered separately from the Monticello Mill Tailings Superfund Site. Approximately 152,000 cy of contaminated material was removed from the Monticello Radioactively Contaminated Properties Superfund Site and transported to an interim stockpile on the former mill site, later to be disposed in the repository at the Monticello Mill Tailings Superfund Site. Most of these properties were cleared for unrestricted future use, and the Monticello Radioactively Contaminated Properties Superfund Site has been delisted from the NPL.

5.2.2 UMTRCA Cleanup Actions

There are an additional ten UMTRCA Title I sites located in the "four corners" states (New Mexico, Arizona, Utah, and Colorado), five of which are located reasonably near the Navajo

Nation to be relevant to this Initial White Paper.[195] All five have disposal cells containing radioactive material (tailings, contaminated soil and building material, demolition debris, etc.) from the mill sites and (in some cases) from vicinity properties. In general, the disposal cells are similar to those at the UMTRCA Title I sites located within the Navajo Nation. Disposal cell details and cap specifications for the five UMTRCA Title I sites located near the Navajo Nation are provided below.

	Ambrosia Lake, NM	Slick Rock, CO	Durango, CO		Naturita, CO	Gunnison, CO
			Top	Sides		
Area (acres)	91	12	42		10	29
Height (feet)	50	50	NR		NR	50
Radon Barrier (inches)	30	18[1]	24[2]	24[4]	36[5]	18[6]
Bedding Layer (inches)	6	6	None	6	6	6
Riprap – Top (inches)	6	8	6[3]	NA	12	6
Riprap - Sides (inches)	12	12	NA	12	12	6
Top slope (percent)	2.5	2 to 3	NR	NR	4	2.5
Side slope (percent)	20	20	NR	NR	NR	NR

NR-Not Reported
NA-Not Applicable
1-The Slick Rock disposal cell also has 24-inch frost-protection layer above radon barrier.
2-The top of the Durango disposal cell also has a 6-inch drain/filter layer/bentonite mat, an 18-inch bio intrusion layer, and a 30-inch frost-protection layer above the radon barrier.
3-The top of the Durango disposal cell is a 6-inch rock/soil matrix.
4-The sides of the Durango disposal cell also have a 6-inch drain layer, 6-inch bedding layer, and 18-inch frost-protection layer above the radon barrier.
5-The Naturita disposal cell also has a 66-inch frost-protection layer above the radon barrier.
6-The Gunnison disposal cell also has a 72-inch frost-protection layer and a second 6-inch bedding layer above the radon barrier.

There are also two UMTRCA Title II sites located near the Navajo Nation at which NRC-approved reclamation/cleanup activities have been completed (the Bluewater and L-Bar Disposal Sites, both located in Cibola County, New Mexico). At both sites, tailings and other contaminated material were consolidated and placed in on-site disposal cells built atop existing tailings piles. These disposal cells are not as robust as those built for the Title I

[195] The ten UMTRCA "sites" actually represent 20 distinct physical sites, generally comprising a former processing site and an off-site disposal cell. One "site" (Slick Rock, Colorado) has two processing sites, and at another (Ambrosia Lake) the disposal cell is located at the former mill site.

sites, but comply with NRC reclamation and cleanup standards nonetheless.[196] At the Bluewater site, there are seven disposal cells, reflecting the variety of waste found there. The main tailings pile (for acid tailings), a second tailings pile (for basic tailings), and a cell for PCB-containing radioactive waste are all capped with a two-layer cover consisting of a low-permeability radon barrier layer and a riprap erosion-protection layer. The other four cells are covered by a radon barrier topped by either a soil-rock matrix layer or topsoil, both seeded with native grasses. The L-Bar disposal cell is covered with a 4.1-foot- thick radon barrier (compacted clay) and top layer of soil ranging in thickness from 2 to 6 feet. The side slopes of the disposal cell are armored with riprap for erosion protection.

[196] NRC's reclamation and cleanup standards (10 CFR Part 40, Appendix A) conform to USEPA's standards at 40 CFR 192.

6.0 LESSONS LEARNED AND OPTIONS FOR THE CLEANUP OF AUMS ON THE NAVAJO NATION

As summarized in Section 5, cleanup performed to date at AUMs and other uranium-related sites in and near the Navajo Nation has been limited, for the most part, to excavation of contaminated soil, waste rock, tailings, and other materials and consolidation of the excavated materials in a disposal cell located at the site (typically atop an existing waste pile) or in a repository built nearby.[197] This reflects in part the interim nature of some of the cleanup, but it also reflects the fact that containment is the only type of general cleanup action suitable for addressing AUM waste and other uranium-related waste.[198] This section discusses some of the lessons learned as a result of the cleanup actions performed to date and identifies the process/design options available for containing AUM waste. Together, this information can be used as a basis for future decisions made with respect to cleanup of AUMs in the Navajo Nation.

NNEPA has expressed strong support for a policy that favors removal of all uranium waste from the Navajo Nation. As stated by former NNEPA Executive Director, Stephen B. Etsitty, "*This policy has arisen from the Navajo Nation's long experience with the legacy of uranium mining within the Navajo Nation. The policy is designed to reduce the impact of uranium mining waste on significant customs and cultural values that are unique to the Navajo people. The policy is also the result of the risks to human health and the environment from uranium mine waste.*" In addition, while it is not within the scope of this Initial White Paper to develop a full analysis of the advantages and disadvantages of the option, including removal of all uranium waste from the Navajo Nation, it is important to note that considerations at the various AUMs may vary. Differences that could be important include waste volume, accessibility, topography, degree of radioactivity, proximity of water bodies and residences, proximity of underlying uranium ore bodies to the surface and other

---

197 The term "repository" as used herein means an engineered disposal cell which includes both a liner and an engineered cap that is built in an off-site location or in an on-site area not significantly impacted by AUM waste. A disposal cell built atop a previously existing tailings pile or AUM waste pile is not considered a repository because it does not include a liner. Note also that as used herein, a disposal cell is different from a repository in that it does not include a liner..

198 Available documentation for the uranium cleanup actions at and near the Navajo Nation rarely includes evaluation or even discussion of other cleanup approaches. Of all the documents reviewed by Roux Associates, only the EE/CA for the San Mateo Mine includes a discussion of other approaches, and these were all summarily dismissed on account of their technical or administrative infeasibility. Notable among the approaches dismissed on account of administrative infeasibility is excavation with off-site disposal.

factors. As stated earlier, future work could include in-person meetings to discuss the options with the Uranium Commission and the Navajo people.

6.1 Lessons Learned

A number of lessons can be learned from the cleanup actions already conducted at AUMs and other uranium-impacted sites both within[199] and outside the Navajo Nation.[200] Generally speaking the lessons learned fall into the following three broad categories:

- Problems With Revegetation;
- Long-Term Integrity of Disposal Cells; and
- Cost

Each category is discussed below.

6.1.1 Problems With Revegetation

Not surprisingly given the arid climate of the Navajo Nation, vegetation of constructed caps and revegetation of areas disturbed by cleanup action has been difficult at several sites, including the Skyline Mine, San Mateo Mine, and Cove Transfer Station 1. To some extent, the difficulty in establishing native vegetation at sites is due to normal climatic variability. For example, revegetation of the San Mateo Mine was very slow at first given the very dry conditions experienced in 2013, but has improved more recently with the return of more regular precipitation patterns. However, the success of revegetation is also influenced by the quality of the soil used in capping or restoration. At both the Skyline Mine and Cove Transfer Station 1, soil with an inadequate amount of organic matter was used, and revegetation was not successful.

[199] Cleanup actions within the Navajo Nation include: **NECR and Quivira Church Rock #1 Mines:** Consolidation of AUM waste within a stockpile covered with a temporary soil cap; **Skyline Mine**: Consolidation of AUM waste into a fully encapsulated repository at the AUM; **Cove Transfer Stations and Section 32 Mine:** Consolidation of AUM waste and stabilization of stockpile with tackifier; **UMTRCA (Shiprock, Tuba City, Monument Valley, Mexican Hat and Church Rock):** Consolidation of uranium mill tailings in capped disposal cells at the former mill sites; and **Highway 160:** Contaminated materials excavated and transported outside the Navajo Nation for final disposal.

[200] Cleanup actions outside the Navajo Nation include: **San Mateo Mine**: Consolidation of AUM waste on-site in a capped disposal cell; **Superfund Sites (Homestake, Uravan, Monticello):** Consolidation of uranium mill tailings in capped (and lined in one case) disposal cells at or near the former mill sites; and **UMTRCA (Ambrosia Lake, Slick Rock, Durango, Naturita, Gunnison, Bluewater, and L-Bar):** Consolidation of uranium mill tailings in capped disposal cells at the former mill sites.

Experience at other sites demonstrates that given time, caps and disturbed areas can be successfully vegetated. But they cannot be allowed to simply vegetate on their own: frequent and sometime extensive maintenance and repair is often needed. Vegetated caps are aesthetically superior to armored caps, but they require a greater amount of maintenance and repair.

6.1.2 Long-Term Integrity of Disposal Cells

The long-term integrity of disposal cells, where used to contain waste at or near a site, is of paramount importance to the long-term protectiveness of the remedy. At all of the sites in or near the Navajo Nation at which uranium waste was placed in an engineered disposal cell as part of a cleanup action (i.e., not including the NECR Mine, Quivira Church Rock #1 Mine, Cove Transfer Station #2, or the Section 32 Mine), the disposal cell was capped with a multi-layer cover designed primarily to (1) provide protection against gamma/radon emissions and (2) ensure the long-term integrity of the disposal cell. Accordingly, all of the sites with capped disposal cells feature one or more protective layers to ensure the long-term integrity of the cell:

- At several sites, a rock bio-barrier layer was included as a deterrent to deep-burrowing animals. The riprapped surfaces on many of the UMTRCA Title I disposal cells perform the same function.

- A frost-protection layer is featured at many sites, to protect the underlying radiation barrier from damage due to freeze-thaw cycles.[201]

- An erosion-protection layer was included in most of the covers to prevent erosion of the cover from wind and rain, while others relied on vegetation to provide the necessary stability. The composition of the erosion-protection layer varies from site to site, with some covers featuring a surface layer of riprap or a gravel veneer, and others using a soil/gravel admixture layer at the top of the cap. The table below indicates which sites have which type of erosion protection.

[201] At some sites, no frost-protection layer was specified, but the overall thickness of the cover provided the necessary protection against freeze-thaw damage.

Erosion Protection Components of Disposal Cell/Repository Covers		
None (Unarmored Soil)	**Gravel Admixture**	**Riprap/Gravel Veneer**
• Skyline Mine[1] • Monticello Mill Tailings Superfund Site[1,2] • Bluewater Disposal Site ("Disposal Area No. 1" and two small landfills) • L-Bar Disposal Site (top only)	• San Mateo Mine • United Nuclear Corporation Superfund Site • Durango Disposal Site (top only)[1,2] • Bluewater Disposal Site (asbestos cell only)	• Shiprock Disposal Site • Tuba City Disposal Site • Mexican Hat Disposal Site • Uravan Uranium Project Superfund Site[2] • Ambrosia Lake Disposal Site • Slick Rock Disposal Site[2] • Durango Disposal Site (side slopes only)[2] • Naturita Disposal Site[2] • Gunnison Disposal Site[2] • Bluewater Disposal Site (tailings disposal cells and PCB/radioactive waste cell) • L-Bar Disposal Site (side slopes only)

1-These covers also included a rock bio-barrier.
2-These caps also included a frost-protection layer.

Based on Roux Associates' review of available information, bio-intrusion (animal burrowing) does not appear to be a problem at sites with bio-barriers; however, it likewise does not seem to be a problem at sites without bio-barriers (and without riprap surfaces). Therefore, no conclusion can be drawn with respect to their effectiveness and whether or not the added cost for a bio-barrier is justified. It is likewise difficult if not impossible to evaluate the effectiveness of (and hence the justification for) the frost-protection layers, given that the radiation barriers cannot be inspected for cracking due to freeze-that cycles, any leakage of radon from the radiation barrier (if cracked) would likely be attenuated by the frost-protection layer, and it would be impossible to determine if leachate generation or increases in uranium concentrations in underlying groundwater were attributable to the inadequacy of a frost-protection layer. Instead, the primary lessons learned with respect to construction of disposal cells and repositories pertain to the erosion protection layers, or lack thereof.

With respect to the erosion-protection layers, the sites with riprap/gravel covers appear to have experienced less erosion than those with admixture covers or soil covers only. However, the admixture covers-and even most of the soil covers, particularly where well vegetated-seem to have experienced only minor erosion, although some of those covers are still relatively new and so have not been subject to erosion for a long period of time. (The eroded soil cap at the Quivira Church Rock #1 [see photograph in Section 5] is a good example of what can happen to a poorly vegetated soil cap over a long period of time.) Unarmored and un-vegetated (or not-yet-vegetated) caps, such as those at the Skyline Mine and Cove Transfer Station #1 (as well as the uncapped stockpiles at the Section 32 Mine and at Cove Transfer Station #2), have experienced the most erosion.

At the same time, however, while they provide the greatest protection against erosion, riprap caps are the least aesthetically appealing, as they do not blend at all into the landscape, but rather stand out as long-lasting and stark reminders of the unwanted legacy of uranium mining. Admixture caps provide a reasonable compromise between the need for erosion protection and aesthetics. Although they are subject to some erosion, as seen at the San Mateo Mine, this is somewhat by design, in that they contain both a soil component needed to provide a rooting medium for plants to grow on the cap and sufficient gravel to provide the necessary armoring against significant erosion (even if some or all of the soil is eroded away). For further details regarding admixture caps, see articles published by Professor Clifford Anderson[202,203,204] provided in **Appendix B**.

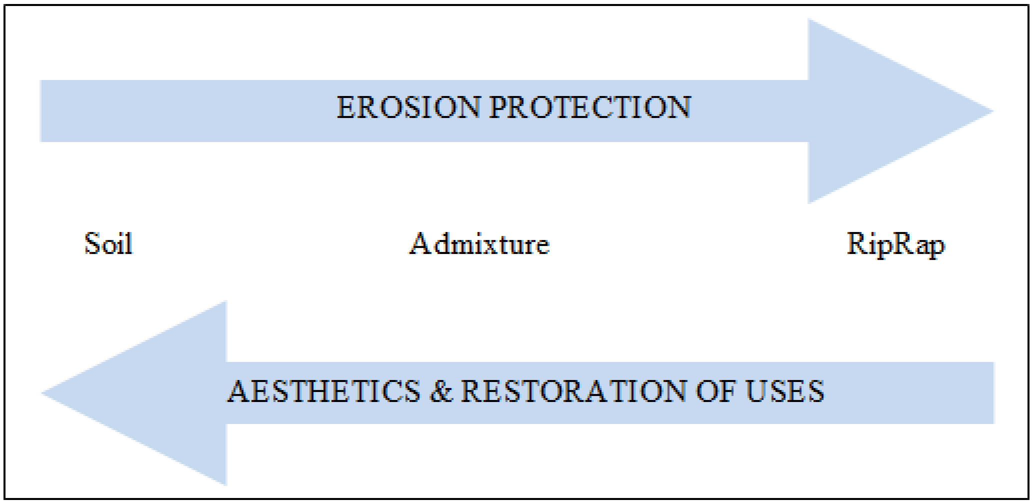
The long-term integrity of disposal cells, where used to contain waste at or near a site, is of paramount importance to the long-term protectiveness of the remedy. While caps composed of soil with vegetative cover most closely represent pre-mining terrain, they require the most maintenance to ensure long-term protectiveness, given their greater susceptibility to erosion. Admixture and riprap afford progressively greater protection from erosion but at the same time are progressively more obtrusive and limiting with respect to future use of the site. This tradeoff between aesthetics and erosion is depicted in the figure which follows.

---

202 C. Anderson and J. Stormont, "Gravel Admixtures for Erosion Protection in Semi-Arid Climates," Erosion of Soils and Scour of Foundations, Proceedings of the Geo-Frontiers, 2005, IN Geotechnical Special Publication No. 135, American Society of Civil Engineers, Reston VA; 2005; ISMB 978-0-7844-0781-3.

203 C. Anderson and S. Wall, "Design of Erosion Protection at Landfill Areas with Slopes less than 10%," Geotechnical Special Publication No. 210, Scour and Erosion, Proceedings of the Fifth International Conference on Scour and Erosion (ISE-5); November 7-10, 2010, San Francisco, USA; ISBN 978-0-7844-1147-6.

204 C. Anderson and S. Wall, "Erosion Protection at Landfill Slopes Greater than 10%," Geotechnical Special Publication No. 210, Scour and Erosion, Proceedings of the Fifth International Conference on Scour and Erosion (ISE-5); November 7-10, 2010, San Francisco, USA; ISBN 978-0-7844-1147-6.



Considerations for Armoring

Riprap may also allow greater infiltration compared to soil/vegetative cover and thus require incorporating additional components (e.g., HDPE liner) into the cap design, which may increase costs. However, if a soil cap is preferred in lieu of more armored caps for aesthetics or restoration of uses reasons (e.g., grazing and other Navajo traditional practices), sufficient funds may need to be budgeted for maintenance and repair of the cap in perpetuity (more so than for an armored cap). It may be less expensive in the long run to build a less expensive soil cap with allowance made for periodic maintenance and repair; a detailed cost analysis (which is beyond the scope of this White Paper) would be needed to determine if this is, in fact, the case.

6.1.3 Cost

Based on information made available to Roux Associates, the various cleanup actions performed to date at AUMs in and near the Navajo Nation have cost between roughly $1 million and $10 million. The cost range reflects a number of variables, including the volume of contaminated material excavated, the method of disposal, the disposal location, and logistical factors. One cost that stands out is that for the Tuba City Highway 160 Site ($5 million). As discussed in Section 5, this was the only site within the Navajo Nation for which excavated uranium waste was disposed outside the Navajo Nation. And while the total cost for the cleanup action performed there ($5 million) was not particularly high compared to the other cleanup actions-it falls right in the middle of the range of costs-the overall scope of the cleanup action was relatively small (only 6,000 cy of contaminated material was excavated). As a result, the weighted cost of the cleanup action (i.e., cost per cubic yard of material removed), about $830/cy, is far greater than that for any other uranium site within the Navajo Nation. Had more contaminated material been removed, the cost for the Highway 160 Site would have been much higher.

Another project with a relatively high weighted cost (~$300/cy) is the Skyline Mine removal action. The cost for this cleanup action appears to have been driven to a large degree by the logistical difficulties involved (e.g., construction of access road to the top of mesa, use of a cable yarder to transport waste to the top of the mesa). But another important factor contributing to the relatively higher weighted cost was the decision to line and cap the repository with HDPE geomembranes. For future cleanups, the added value of a lined repository (e.g., increased protection of groundwater, increased public/cultural acceptance) must be weighed against the cost involved.

6.2 Cleanup Options for AUMs

Both the federal and Navajo Nation CERCLA require that cleanup actions be protective of human health and the environment, be cost-effective (taking into account both short- and long-term costs), and utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable. As discussed above, containment is the only type of general cleanup action suitable for addressing AUM waste. Under the general category of containment, there are only two process options available:

- Containment of the waste at the AUM (with or without excavation); or
- Containment of the waste elsewhere (either on or off the Navajo Nation).[205]

Both of these options are, to varying degrees, protective of human health and the environment and cost-effective, and both utilize permanent solutions to the extent practicable.

<u>Containment at the AUM</u>

Although NNEPA has expressed strong support for a policy favoring removal of all uranium waste from the Navajo Nation, containment of AUM waste at the AUM (with or without

[205] As discussed in Section 3 of this White Paper, notwithstanding the Navajo Nation's desire to remove uranium-impacted material from Navajo land, under some circumstances the use of engineered containment cells or repositories to manage AUM waste on Navajo land should be within the framework of Navajo Fundamental Law, which is based on experience rather than a set of rules.

excavation) is the most direct and cost-effective approach to address AUM waste assuming site conditions, public sentiment, and engineering logistics permit such an approach.[206] Available cleanup alternatives under this process option include capping the waste in-place without excavation, consolidating the waste into a smaller area (i.e., atop existing waste), or excavating the waste for consolidation in a new repository at the AUM. Generally speaking, capping AUM waste in-place is the least expensive and most easily implemented alternative for any given site, provided the waste is not widely disseminated, because it does not entail the extensive handling of contaminated material. Excavation of outlying waste and consolidation into a smaller area would be slightly more expensive. Both are adequately protective, in that they involve the covering of contaminated material to prevent (1) exposure to human and/or ecological receptors and (2) offsite migration via airborne or storm water transport. Construction of a new repository at the AUM would add further to costs but would also provide the added benefit of permitting the waste to be fully encapsulated with a cap and liner.

Containment of AUM waste at the AUM may likely limit future use of the AUM site, with the extent of such limitation being highly dependent on the design of the cover for the disposal cell or repository for the AUM waste. There are multiple options available with respect to the design of the cover. Restrictions on future use for housing and future use of groundwater in the vicinity of the AUM would most likely be required for any design; however, many other uses, including most traditional Navajo uses, would likely be permissible for most designs provided that adequate radiation shielding (as determined, for example, by the PRG calculator[207] or other suitable risk assessment approach) is provided and maintained in perpetuity. Armoring of the cover for erosion protection could potentially preclude certain future uses, such as grazing.

<u>Containment Elsewhere</u>

Where site conditions, engineering logistics, and/or public sentiment do not favor containing the AUM waste at the AUM, then radiological-impacted materials can be excavated and contained elsewhere, either within or outside the Navajo Nation (as noted earlier, NNEPA

---

[206] This statement assumes that funding for perpetual maintenance is available, as would be required for both containment at the AUM and containment elsewhere (if on the Navajo Nation).

[207] The Preliminary Remediation Goals (PRGs) for Radionuclides electronic calculator, known as the Rad PRG calculator is described at http://epa-prgs.ornl.gov/radionuclides/ and discussed in USEPA's June 14, 2014 memorandum on "Radiation Risk Assessment at CERCLA Sites: Q&A" at http://nepis.epa.gov/Exe/ZyPDF.cgi/P100K3TC.PDF?Dockey=P100K3TC.PDF

has expressed strong support for a policy that favor removal of all uranium waste from the Navajo Nation). For containment within the Navajo Nation, four cleanup alternatives are available: (a) containment near the AUM (e.g. at a nearby AUM or other acceptable nearby location), (b) containment in a local repository, (c) containment in a regional repository or (d) containment in a single, centralized repository. And for each alternative, there are multiple options with respect to the design of the containment, including lining, leak detection, and capping, allowing for a wide range in the level protection provided. Regardless of which cleanup alternative and design are selected, the cost for containment elsewhere within the Navajo Nation will likely always be higher than the cost for containment at the AUM, because containment elsewhere entails loading and transporting the contaminated material potentially significant distances; the greater the distance the waste is transported, the greater the cost. At the same time, however, with containment elsewhere within the Navajo Nation, the option always exists to fully encapsulate the contaminated material (allowing for greater isolation of the AUM waste), whereas that option is limited when containing waste at the AUM. In all instances, long-term inspection and maintenance is needed to ensure that the containment of the waste is protective of human health and the environment and consistent with Navajo Fundamental Law in perpetuity.

Although containment elsewhere within the Navajo Nation could allow for unlimited future use of the AUM site (groundwater use may still have to be restricted, and NORM or TENORM may become exposed once the AUM waste is removed, limiting future use), it could result in limitation of the future use of the containment site, be it another AUM or a local, regional, or central repository. As with the limitations associated with containment at an AUM, the limitations on future use associated with off-site containment would be highly dependent on the design of the cover for the disposal cell/repository. However, the number of such sites and the overall acreage requiring limitations would likely be smaller with off-site containment (except if all AUM waste were moved to a nearby repository on a one-to-one basis).

For containment outside the Navajo Nation, two cleanup alternatives exist: disposal (with eventual containment) at an UMTRCA Title II facility or disposal (with eventual containment) at a licensed radioactive waste disposal facility. Although both are more consistent with Navajo Nation policy with respect to the disposition of uranium waste existing within the Navajo Nation and could allow for unrestricted future use of AUM sites (assuming any other existing hazards, such as safety hazards, are also adequately addressed and NORM/TENORM is not exposed as a result of the removal of AUM waste),[208] containment outside the Navajo Nation is likely to be more costly than containment within the Navajo Nation.[209] As discussed above, removal of uranium waste from the Tuba City Highway 160 Site to a location outside the Navajo Nation resulted in a weighted cleanup cost of roughly $830/cy, far more than for any other cleanup performed within the Navajo Nation (or being evaluated),[210] in large part because of the long transportation distance involved in disposing of the waste.[211] Had more contaminated material been removed, the cost for the Highway 160 Site would likely have been much higher. A major drawback of containment outside the Navajo Nation, therefore, is that it could limit the number of AUMs that can be addressed given available funds.

6.2.1 Federal CERCLA and Navajo Nation CERCLA Requirements for Selecting Cleanup Alternatives

The Navajo Nation CERCLA (Title 4, Navajo Nation Code, Chapter 17) provides for, among other things, the containment and removal of hazardous substances, pollutants, and contaminants on sites in the Navajo Nation. It sets forth in §2305 (Response action selection), at paragraph H (Requirements for Remedial Actions), the following considerations that must be taken into account when evaluating remedial alternatives/options:

- The long-term uncertainties associated with land disposal;
- The goals, objectives, and requirements of the Navajo Nation Solid Waste Code;

208 Future use of groundwater in the vicinity of the AUM may still have to be restricted.

209 It is possible that containment at an UMTRCA Title II facility located outside the Navajo Nation could be less costly than containment within the Navajo Nation, but only if the facility is located relatively close to the AUM. Although loading and transportation costs would be involved, costs for containment would not be involved as they would be borne by the operator of the facility at the time of facility closure.

210 Mark Ripperda of USEPA provided Roux Associates with a spreadsheet showing the total and weighted costs for several of the cleanup actions performed in the Navajo Nation, as well as the estimated and weighted costs for some cleanup alternatives being evaluated. Roux Associates was able to calculate weighted costs for the Skyline Mine and the Section 32 Mine based on available documentation and personal communication with the USEPA On-Scene Coordinator, respectively.

211 Roux Associates was not provided with detailed cost information for the Highway 160 cleanup action, so the actual cost driver(s) are not known at this time. The weighted costs for other cleanup actions involving or potentially involving transport of waste (e.g., Cove Transfer Stations, Quivira Mines) are also relatively high compared to other cleanup actions, but they are not nearly as high as for the Highway 160 Site. That may be because the higher soil volumes associated with those cleanup actions dilute the total cost to some extent; nevertheless, it is not unreasonable to conclude that greater the distance excavated wastes are transported, the greater will be the costs.

- The persistence, toxicity, mobility, and propensity to bioaccumulate of such hazardous substances, pollutants, or contaminants and their constituents;

- Short- and long-term potential for adverse health effects from human exposure;

- Long-term maintenance costs;

- The potential for future remedial action costs if the alternative remedial action in question were to fail; and

- The potential threat to human health and the environment associated with excavation, transportation, and re-disposal, or containment.

These requirements parallel those found in the federal CERCLA statute, which also specifies (through the National Contingency Plan) additional criteria for the evaluation of cleanup alternatives, including implementability, cost, and community acceptance. Although this White Paper does not provide a detailed comparison of the various cleanup alternatives identified above pursuant to all of the evaluation criteria specified under either the federal or Navajo Nation CERCLA due to time and budget constraints, Roux Associates did consider these criteria in identifying the particular advantages and disadvantages of the two main process options and the associated cleanup alternatives, as set forth below.

6.2.2 Decision Framework for Process Options and Cleanup Alternatives

There are five major factors to consider in selecting a cleanup alternative for an AUM:

(f) **Location:** Decision-makers need to consider whether or not to contain the AUM waste at the AUM or to excavate and dispose of it elsewhere (either on or off the Navajo Nation). Containment at the AUM may be favored where the AUM is readily accessible for periodic inspection and monitoring, local roads are adequate for repeated heavy vehicle access (e.g., for ongoing maintenance), the terrain supports cap construction and maintenance, and where NORM or TENORM would be exposed if the AUM waste were to be removed. Conversely, the engineering controls need to safely contain waste at the AUM are more challenging, where residents live or surface water features exist near the AUM, where groundwater is near AUM is used for drinking water, and/or where local climatological conditions (e.g., freeze/thaw cycles, higher precipitation) may increase the cost for cap construction and containment relative to the cost and disruption to transport the waste elsewhere. In such cases, AUM waste excavation and disposal elsewhere may be the preferred alternative.

(g) **Full or partial encapsulation:** If the waste is to be excavated and contained at the AUM, a determination is needed as to whether or not the disposal cell in which the waste is to be contained should be lined. While the disposal cell must always include a surface cover as a radiation shield, decision-makers must also evaluate the need for a liner to provide further groundwater protection (i.e., beyond that provided by the cover). In addition full encapsulation of the waste may address cultural perspectives, for example by fully containing the Yellow Monster (*Leetso)*.

(h) **Armoring and drainage**: The cover design for a disposal cell or repository must attempt to strike a balance between protection (i.e., ensuring the long-term integrity of the cover), aesthetics, and future land use. Knowing that storm water can result in channelization and erosion, covers should be designed with an understanding of potential future channel erosion so that the cover which remains after such erosion is still sufficiently protective. This may require significant armoring, which could in turn detract from aesthetics and/or limit future use (see next item).

(i) Future Use: Decision-makers need to consider whether and to what extent cleanup alternatives that entail containment of AUM waste within the Navajo Nation might limit future use of an AUM site or other Navajo land (in the case of an off-site repository). Most alternatives involving containment within the Navajo Nation may require certain restrictions on future use (e.g., precluding residential use and use of groundwater); however, most would allow for restoration of uses, including many traditional Navajo uses (herb gathering etc.), provided that adequate radiation shielding (as determined, for example, by the PRG calculator or other suitable risk assessment approach) is provided and maintained in perpetuity. However, off-site disposal does not always result in unlimited future use of an AUM site, as NORM or TENORM may become exposed once the AUM waste is removed.

(j) **Future inspection and maintenance to ensure long-term integrity**: The long-term integrity of AUM waste disposal cells and repositories is of paramount importance to the long-term protectiveness of the selected remedy. Soil and admixture covers need to be periodically inspected and repaired if erosion and/or other damage are evident. In order for soil and admixture covers to be sustainable, they need to be periodically inspected and maintained. While vegetation typically improves the aesthetics and the potential for restoration of tradition uses of the land on which a cap is constructed, establishing native vegetation at sites is difficult because of normal climatic variability and potential die-off during drought. Frequent and sometime extensive maintenance and repair may be needed. This needs to be considered and addressed as part of a long-term inspection and maintenance program.

To assist decision-makers in evaluating the various process options and cleanup alternatives available for addressing AUM waste in the Navajo Nation, several flowcharts are provided herein which show key decision points (yellow diamonds), associated outcomes (green circles), and final disposition (pink hexagons). For each decision point, one or more important considerations ("decision factors") come into play; certain factors may favor one direction (the "yes" arrow in the flowchart), while others may favor the opposite direction (the "no" arrow). Ultimately, the decisions made will likely be dictated by consideration of all of the factors taken as a whole and the associated critical thinking in the decision-making process.

The decision framework for selection of a cleanup alternative is presented as a series of four flowcharts:

- **Chart 1 (AUM Cleanup – Contain at AUM or Elsewhere)** shows the decision points and potential outcomes with regard to whether or not the AUM waste is to be contained at the AUM and how it is to be contained.

- **Chart 2 (Liner Design Sequence)** contains the decisions and potential outcomes associated with a lined repository ("liner sequence") if a cleanup alternative involving a repository is selected.

- **Chart 3 (Cap Design Sequence)** contains the decisions and potential outcomes associated with cap design ("cap sequence") when the waste is to be contained within the Navajo Nation.

- **Chart 4 (Disposal Elsewhere Sequence)** contains the decisions and potential outcomes with regard to whether or not to contain AUM waste within the Navajo Nation (when it is not to be contained at the AUM) and, if so, where.

The four flowcharts taken together allow various process and design options including (a) location for disposal, (b) cover design, (c) whether a liner is warranted, and (d) whether leak detection is warranted. These options impact the degree and frequency of future monitoring, maintenance, and repair required for the selected alternative.

Chart 1: AUM Cleanup – Contain at AUM or Elsewhere?

The first major decision point in the section of a cleanup approach for a given AUM (from which all other decisions follow) is whether or not the AUM waste should be consolidated at the AUM or elsewhere. The table below provides the key considerations affecting this decision, including proximity to residents and surface water bodies, local use of groundwater, accessibility, site terrain and climate, and the potential exposure of NORM or TENORM if the AUM waste is removed. The considerations are presented in the form of questions, the possible answers to which ("yes" or "no") support one or the other of the two possible pathways shown on the flowchart for that decision point. The respective pathways supported for both "yes" and "no" answers are indicated in the table.

Decision Factors for Containment at the AUM			
Example[212] Decision Factors	**Answer**	Contain at AUM? Flowchart Pathway Yes (Contain at AUM)	 Flowchart Pathway No (Contain Elsewhere)
Do any residents live within ¼ mile of AUM?	Yes		✓
	No	✓	
Are there any surface water features within ¼ mile of AUM?	Yes		✓
	No	✓	
Is groundwater within 1 mile of AUM used for drinking water and/or livestock watering?	Yes		✓
	No	✓	
Is AUM relatively easy to access (for periodic inspections/monitoring)?	Yes	✓	
	No		✓
Are local roads adequate for repeated heavy vehicle access (e.g., for ongoing maintenance)?	Yes	✓	
	No		✓
Does terrain support cap constructability/maintenance?	Yes	✓	
	No		✓
Will local climatological conditions (e.g., freeze/thaw cycles, higher precipitation) increase cost for cap construction beyond cost to transport waste elsewhere?	Yes		✓
	No	✓	
Will NORM or TENORM be exposed if AUM waste is removed?	Yes	✓	
	No		✓

As the table above indicates, containment at the AUM is favored where the AUM is readily accessible for periodic inspection and monitoring, local roads are adequate for repeated heavy vehicle access (e.g., for ongoing maintenance), the terrain supports cap construction and maintenance, and NORM or TENORM would be exposed if the AUM waste were removed. Conversely, containment at the AUM is not supported where residents live or

[212] The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

surface water features exist near the AUM, groundwater near the AUM used for drinking water and/or livestock watering, or local climatological conditions (e.g., freeze/thaw cycles, higher precipitation) may tend to increase the cost for cap construction beyond the cost to transport the waste elsewhere.

If containment at the AUM is supported, the next decision that has to be made is whether or not to excavate and consolidate the AUM waste or simply cap the AUM waste without consolidation. As shown in the table below, two factors affect this decision: (1) whether or not the AUM waste is widely disseminated throughout the AUM and (2) whether or not NORM or TENORM would be exposed if the AUM waste is consolidated.

Decision Factors for Excavation and Consolidation

Example[213] Decision Factors	**Answer**	Excavate and/or consolidate? Flowchart Pathway: Yes (Cap after excavating and/or consolidation)	No (Cap in-place without excavation and/or consolidation)
Is AUM waste widely disseminated?	Yes	✓	
	No		✓
Will NORM or TENORM be exposed if AUM waste is consolidated?	Yes		✓
	No	✓	

If containment at the AUM and excavation/consolidation of the waste are both supported, the next question to be asked is whether or not the waste should be contained in a new repository (i.e., lined and capped disposal cell) at the AUM or simply contained within the existing footprint of the AUM waste. As shown in the table below, the factors influencing this

213 The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

decision include (a) whether or not further groundwater protection is warranted (keeping in mind that adequate groundwater protection may be afforded by the cap design alone), (b) whether or not full encapsulation of the waste is necessary or desirable to address cultural perspectives, and (c) whether or not there is adequate available space at the AUM to build a repository.

Decision Factors for New Repository at AUM			
Example[214] Decision Factors	**Answer**	New repository at AUM? Flowchart Pathway: Yes (New repository with potential liner)	No (Cap constructed within existing footprint of AUM waste)
Is further groundwater protection warranted?	Yes	✓	
	No		✓
Is full encapsulation of the waste necessary or desirable to address cultural perspectives by fully containing the Yellow Monster (*Leetso*)?	Yes	✓	
	No		✓
Is there adequate available space at the AUM to build a repository without entailing significant excavation and temporary relocation of the AUM waste?	Yes	✓	
	No		✓

If containment at the AUM is not supported, and thus the waste is to be excavated and contained or disposed elsewhere (either within or outside the Navajo Nation), a determination is needed as to whether or not the containment should be lined (if disposal is within the Navajo Nation). As shown in the table below, the factors influencing this decision are the generally the same as for the new repository at the AUM, except that available space is not a consideration.

214 The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

<table>
<tr><th colspan="4">Decision Factors for Lined Containment</th></tr>
<tr><th rowspan="3">Example[215] Decision Factors</th><th rowspan="3">Answer</th><th colspan="2">Liner desired or warranted?</th></tr>
<tr><th colspan="2">Flowchart Pathway</th></tr>
<tr><th>Yes
(Liner included in cap design)</th><th>No
(Liner not included in cap design)</th></tr>
<tr><td rowspan="2">Is further groundwater protection warranted?</td><td>Yes</td><td>✓</td><td></td></tr>
<tr><td>No</td><td></td><td>✓</td></tr>
<tr><td rowspan="2">Is full encapsulation of the waste necessary or desirable to address cultural perspectives by fully containing the Yellow Monster (Leetso)?</td><td>Yes</td><td>✓</td><td></td></tr>
<tr><td>No</td><td></td><td>✓</td></tr>
</table>

Chart 2 (Liner Design Sequence) and Chart 3 (Cap Design Sequence)

The decisions contained in Chart 1 (to contain the waste at the AUM or elsewhere) are strategic in nature. Once these strategic decisions have been made, some principal design decisions have to be made with respect to (a) the need for a double liner if the repository is to be lined and (b) the design of the cap for the disposal cell or repository.

Chart 2 shows the principal design decision that has to be made with respect to the design of the containment liner if a lined repository is to be built. This decision is whether or not the repository should be double-lined, and as shown in the table below, the factors influencing that decision include whether or not the additional protectiveness of a second liner is technically warranted, desired, and cost-effective and whether or not the ability to detect leaks in the primary liner is a desirable feature of the design.

[215] The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

Decision Factors for Double-Lined Repository			
Example[216] Decision Factors	Answer	Double-Lined Repository?	
		Flowchart Pathway	
		Yes (Double liner included in cap design)	No (Single liner included in cap design)
Is the added protectiveness of a second liner technically warranted?	Yes	✓	
	No		✓
Is the added protectiveness of a second liner desired?	Yes	✓	
	No		✓
Is the added protectiveness of a second liner cost-effective?	Yes	✓	
	No		✓
Is the ability to detect leaks in the primary liner is desired?	Yes	✓	
	No		✓

Chart 3 shows the principal design decisions needed to design the containment cap, whether it be for a capped in-place waste pile, waste consolidated atop existing waste (within the existing footprint of the AUM waste), or a newly built repository. As the cap design involves a sequence of decisions, multiple tables are provided below, showing the decision factors for each step in the sequence. Cap design decisions include:

- The depth of soil or other cover needed to provide adequate radiation shielding (as determined for example by the PRG calculator or other suitable risk assessment approaches);

- The need for further groundwater protection in the cap design using high density polyethylene (HDPE) cover, evapotranspiration (ET) cover and or a Capillary barrier.

[216] The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

- The need for frost protection by including a frost protection;
- The type and relative amount of armoring used; and
- Funding availability for periodic cap inspection and maintenance.

Cap design may include soil, admixture and riprap in various combinations. The type of material used is dependent upon cap and site features (top slope, edge slope, contributing watershed, historical flooding, etc.) as well as the desired future use of the cap. Cap design also needs to consider whether it can be vegetated and whether such vegetation can survive episodic droughts. The cap design should also consider stormwater flow channelization and associated erosion that may occur over time.

Decision Factors for Cap Sequence – Step 1

Example[217] Decision Factors	**Answer**	Further groundwater protection warranted? Flowchart Pathway	
		Yes (HDPE cover, ET cover or Capillary barrier included in cap design)	No (HDPE cover, ET cover and/or Capillary barrier not included in cap design)
Is groundwater relatively shallow at the containment location?	Yes	✓	
	No		✓
Is groundwater within 1 mile of the containment location used for drinking water and/or livestock watering?	Yes	✓	
	No		✓

217 The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

Decision Factors for Cap Sequence – Step 2			
Example Decision Factor	**Answer**	Frost protection warranted?	
		Flowchart Pathway	
		Yes (Frost protection layer included in cap design)	No (Frost protection layer not included in cap design)
Is the containment location subject to frequent freeze-thaw cycles?	Yes	✓	
	No		✓

Decision Factors for Cap Sequence – Step 3			
Example[218] Decision Factors	**Answer**	High erosion potential?	
		Flowchart Pathway	
		Yes (Riprap/gravel veneer cover included as a major component of the cap design)	No (Riprap/gravel veneer cover not included as a major component of the cap design)
Are any slopes on the containment >10%?	Yes	✓	
	No		✓
Is there significant potential for storm water run-on, even with diversion ditches built uphill?	Yes	✓	
	No		✓

[218] The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

Chart 4: Excavate and Containment Elsewhere

If containment of AUM waste at the AUM is not supported, and the decision has been made to contain the waste elsewhere, the next major strategic decision in selecting a cleanup alternative for the waste is whether or not to contain the waste within the Navajo Nation or dispose of it outside the Navajo Nation (for eventual containment there). The chart below shows some of the key decision factors involved in this decision.

Decision Factors for Containment Within the Navajo Nation

Example[219] Decision Factors	Answer	Contain on Navajo Nation land? Flowchart Pathway	
		Yes (Contain on Navajo Nation land)	No (Dispose outside the Navajo Nation)
Could containment within the Navajo Nation in any way be reconciled with Navajo Nation policy and/or Fundamental Law?	Yes	✓	
	No		✓
Does available funding limit the ability to remove all AUM waste on the Navajo Nation and dispose outside the Navajo Nation?	Yes	✓	
	No		✓
Is it preferred to remove as much AUM waste as possible from the Navajo Nation at the risk of leaving some AUM waste unaddressed?	Yes		✓
	No	✓	
Would there be significance public opposition to permanent local repositories (i.e., near the AUM but in more acceptable locations), regional repositories (i.e., one for each AUM region), or a single, centrally located repository?	Yes		✓
	No	✓	
Can acceptable locations be found for local, regional, or central repositories?	Yes	✓	
	No		✓

219 The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

This decision framework yields six generally viable containment alternatives for AUM cleanup:

Alternative 1: Cap the AUM waste in-place at the AUM, without any excavation or consolidation;

Alternative 2: Excavate/consolidate the AUM waste and contain it at the AUM (within a smaller footprint);

Alternative 3: Excavate/consolidate the AUM waste and contain it in a new repository located at the AUM;

Alternative 4: Excavate/consolidate the AUM waste and contain it at a nearby AUM;

Alternative 5: Excavate/consolidate the AUM waste and contain it in a local, regional or central repository located within the Navajo Nation; or

Alternative 6: Excavate the AUM waste and dispose of it outside the Navajo Nation.

To further streamline the remedy selection process for a particular AUM, **Table 2** that follows lists the minimum requirements (AUM characteristics and other considerations) for each of the six alternatives identified above (including the three sub-options for Alternative 5). These minimum requirements must be met for an alternative to be considered truly viable for a particular AUM. For example, AUM waste at an AUM may need to be limited to one or more discrete piles in order for Alternative 1 (capping in-place at the AUM) to be considered a viable alternative for that AUM. Looked at another way, these requirements are limiting factors, i.e., factors which, if *not* met for a particular AUM, may *preclude* the selection of one or more alternatives for that AUM. For example, if residents live near a particular AUM, alternatives entailing on-site consolidation of AUM waste (Alternatives 1, 2, and 3) may not be appropriate for that AUM. Note that Alternative 6 (excavation with disposal outside the Navajo Nation) has no limiting factors; consequently, this alternative will likely be viable for all AUMs.

Table 2: Screeneing Criteria for AUM Waste Clean-up Alternatives

AUM Characteristics and Other Considerations*	Remedial Alternatives							
	Alternative 1: Cap the AUM waste in-place at the AUM	Alternative 2: Excavate and consolidate the AUM waste and contain it at the AUM	Alternative 3: Excavate and consolidate the AUM waste and contain it in a new repository	Alternative 4: Excavate and consolidate the AUM waste and contain it at a nearby AUM	Alternative 5: Excavate and consolidate the AUM waste and contain it in a:			Alternative 6: Excavate the AUM waste and dispose of it outside the Navajo Nation
					Local Repository	Regional Repository	Central Repository	
No residents within 1/4 mile of AUM	✓	✓	✓					
No surface water within 1/4 mile of AUM	✓	✓	✓					
Groundwater within 1 mile of AUM not used for drinking water and/or livestock watering	✓	✓	✓					
Relatively easy to access (for periodic inspections/monitoring)	✓	✓	✓					
Roads adequate for repeated heavy vehicle access (for ongoing maintenance as needed)	✓	✓	✓					
Terrain supports cap constructability	✓	✓	✓					
Climatological conditions (freeze/thaw cycles, higher precipitation) won't increase cost for cap construction beyond cost to transport waste elsewhere	✓	✓	✓					No limiting factors
Liner not desired/warranted	✓	✓						
Waste limited to discrete pile(s)	✓							
Adequate space at AUM for repository (limited excavation required to build)			✓					
AUM amenable to on-site containment located nearby				✓				
Suitable location for repository nearby					✓			
Suitable location for repository within AUM region						✓		
Suitable centralized location for repository available within Navajo Nation							✓	

* The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

Use of the above table can allow decision-makers to screen the various alternatives listed above before moving forward with a more detailed analysis of alternatives for a particular AUM taking into account variables such as short-term risk and cost. As can be seen, some alternatives may have more minimum requirements than others; as a result, these alternatives can potentially be screened out more often than those with fewer requirements. Alternative 6, which has no limiting factors, typically would not be screened out.

Following the above alternative selection, various design decisions need to be considered to complete the remedy. This includes different cap designs (HDPE membranes, ET caps, capillary barriers, frost protection layers, riprap/gravel veneer covers, soil or admixture covers) that would be considered for all of the alternatives that include containing the AUM waste at a location within the Navajo Nation. Further, where a liner is desired or warranted, there are two primary liner designs (single-lined or doubled-lined) that should be considered. In addition, a variety of possible materials may be considered for lining the containment area. In selecting the cap design, future use of the land upon which the cap is constructed also needs to be considered, ranging from limited restrictions (e.g., only prohibiting residential use) to more stringent restrictions (e.g., precluding most traditional Navajo uses).

Perhaps the most important design consideration is whether or not to armor the cap. The type of material used in cap construction is dependent upon containment/repository features (top slope, edge slope) and site features (contributing watershed, historical flooding, etc.) as well as the desired future use of the cap. Cap design also needs to consider whether it can be vegetated and whether such vegetation can survive episodic droughts. The cap design usually considers storm water flow channelization and associated erosion that may occur over time. Finally, cap design typically needs to consider restoration of uses, such as grazing sheep and growing plants that are important within the Navajo culture.

As discussed earlier in this section, cleanup selection should consider criteria set forth in the National Contingency Plan as well as those provided in the Navajo Nation CERCLA (Title 4, Navajo Nation Code, Chapter 17) including but not limited to the following evaluation criteria set forth in §2305 (Response action selection), at paragraph H (Requirements for Remedial Actions):

- The long-term uncertainties associated with land disposal;
- The goals, objectives, and requirements of the Navajo Nation Solid Waste Code;
- The persistence, toxicity, mobility, and propensity to bioaccumulate of such hazardous substances, pollutants, or contaminants and their constituents;
- Short- and long-term potential for adverse health effects from human exposure;
- Long-term maintenance costs;
- The potential for future remedial action costs if the alternative remedial action in question were to fail; and
- The potential threat to human health and the environment associated with excavation, transportation, and re-disposal, or containment.

For example, the potential short-term risk and disruption of transporting AUM waste from individual AUMs would need to be weighed against the long-term effectiveness of consolidating AUM wastes in regional repositories or in a centralized repository where periodic maintenance could be achieved more cost-effectively than by containment at or near individual AUMs.

The ultimate selection of a cleanup alternative to address AUM waste at each individual AUM will therefore be dependent upon the evaluation criteria set forth in CERCLA, the NCP and the Navajo Nation CERCLA considering multi-faceted and AUM-specific technical and cost considerations in light of the goals to minimize risk and maximize restoring AUMs for The ultimate selection of a cleanup alternative to address AUM waste at each individual AUM will typically be dependent upon the evaluation criteria set forth in CERCLA, the NCP and the Navajo Nation CERCLA considering multi-faceted and AUM-specific technical and cost considerations in light of the goals to minimize risk and maximize AUM restoration for future Navajo traditional use including but not limited to grazing, hunting, herb gathering and ceremonial purposes.

TABLES

Table 1: Summary of Clean-up Performed To Date at AUMs and Other Uranium-Related Sites In/Near the Navajo Nation

Site			Contact Info	Status	Remedial Actions for Soil/Waste Rock/Tailings, etc.	Cap Details (if applicable)	Costs	Lessons Learned/Other Notes
Located Within the Navajo Nation	1	NECR Mine Site	Sara Jacobs (415) 972-3564 jacobs.sara@epamail.epa.gov	●Completed several interim removal actions ●ROD for disposal of mine waste/impacted soil at UNC tailings cells issued ●Currently in the design phase for site remediation (including pre-design studies)	●6K cy of impacted soil from off-site area excavated and disposed off-site (Grandview, ID) ●130K cy of impacted soil removed from off-site areas and temporarily stockpiled in on-site mine waste pile, which was regraded and covered with 6" clean soil ●Plan (pending NRC approval/license amendment) is to move most soil/mine waste (1M cy) on-site over to UNC NPL site and consolidate w/tailings wastes (already capped); small amount to be disposed or reprocessed off-site	●6-inch clean soil cover (temporary)	●$10M+ spent 2008-2012 on interim removal actions ●EE/CA cost estimate for soil/mine waste removal is $44.4M (EPA notes that cost estimate is 5 years old and newer Quivira estimates are higher for similar actions)	
Located Within the Navajo Nation	2	Quivira Mines	Mark Ripperda (415) 972-3028 ripperda.mark@epamail.epa.gov	●Performed interim removal actions (chip-sealed Red Water Pond Road, applied tackifier to shoulders, installed slope erosion controls, and repaired fencing) followed by removal action at Red Water Pond Road ●RSE completed ●EE/CA underway for 350K cy of on-site mining waste	●Removed 17K cy of impacted soil from Red Water Pond Road and temporarily stockpiled on-site (w/6" clean soil cover)	●6-inch clean soil cover (temporary)	●$1.75M spent on soil removal action ●EE/CA estimates for on-site waste pile range from $24 million for on-site consolidation/cover to $120 million for disposal in Utah (also evaluated disposal in regional repository and at UNC)	●EE/CA currently "shelved" as they discuss possibility of moving mine waste to Ambrosia Lake area, which requires negotiations with EPA Region 6
Located Within the Navajo Nation	3	Skyline Mine	Jason Musante (213) 479-2120 musante.jason@epa.gov	●Soil removal action completed	Removed 25K cy of impacted soil from valley floor and upper slope below mine opening and consolidated in lined on-site repository	●HDPE membrane w/rock bio-barrier and soil cover (no additional details available) ●Also lined with HDPE below waste (HDPE layers fused together)	$7.4 million	●EPA fact sheet calls repository "interim," but Five-Year Plan Summary Report refers to Skyline removal action "the first full mine cleanup"
Located Within the Navajo Nation	4	Cove Transfer Stations	Margaret Waldon (415) 972-3987 Waldon.Margaret@epa.gov	●Interim soil removal action completed	●Removed 13,700 cy of impacted soil from Transfer Station (TS) 1 North, TS1 South, and part of TS2 (outside the consolidation area) and consolidated in single stockpile at TS2 ●Stockpile not capped, only sprayed with stabilizing agent and fenced ●Residual contamination at TS1 (North and South) capped with clean soil backfill (thickness not specified, but reported volume of backfill indicates 12-14 inches on average)	●12-14-inch clean soil backfill cover over excavated areas with residual contamination	$3.3 million	●Average cost per yard ($200) much higher than for NECR ($76) or Quivira ($100), which were similar removal actions ●Unclear whether contaminated areas in Navajo Route 33 ROW excavated ●Removal Action Report projected stabilizing agent would break down after one to two years (no update on stockpile status) ●Remobilization needed to repair soil caps (no vegetation established; erosion); unclear if complete
Located Within the Navajo Nation	5	Section 32 Mine	Randy Nattis (415) 972-3053 Nattis.Randy@epa.gov	●Interim soil removal action completed	●Removed 30K cy of impacted soil from mine area and transfer area and consolidated in single stockpile in mine area ●Stockpile initially not capped, only sprayed with stabilizing agent and fenced ●Stockpile subsequently covered with coir fabric and seeded on account of erosion	N/A	~$1.1 million	●Site located in "allotment land," so not amenable for repository ●Mine area "over-excavated," so material at top of stockpile is relatively clean ●Contiguous contamination in Section 33 not addressed during removal action because on private property ●One area of contaminated soil (RA-17) not removed, but rather "sealed" with tackifier ●Significant erosion of stockpile within first year, necessitating remobilization to re-stabilize stockpile (stockpile now revegetating on its own)

Table 1: Summary of Clean-up Performed To Date at AUMs and Other Uranium-Related Sites In/Near the Navajo Nation

Site			Contact Info	Status	Remedial Actions for Soil/Waste Rock/Tailings, etc.	Cap Details (if applicable)	Costs	Lessons Learned/Other Notes
Located Within the Navajo Nation	6	Shiprock Disposal Site		●UMTRA decommissioning completed ●Groundwater remediation ongoing ●Long-term surveillance ongoing	●Tailings and contaminated materials (including some from off-site properties) consolidated in disposal cell built during UMTRA	●12-inch riprap erosion protection layer ●6-inch granular bedding layer (capillary barrier) ●76-inch low permeability radon barrier layer (sandy silty soils)	Not reported	●Institutional controls emplaced to minimize potential risks to human health and the environment, including grazing restrictions, access control for offsite areas, and prohibition on the use of groundwater in certain areas ●Groundwater remediation achieving objectives ●"Windblown sediment has accumulated in the rock cover in several places, which has enhanced vegetation establishment. Woody, deep-rooted shrubs are controlled because they could damage the radon barrier."
	7	Tuba City Disposal Site		●UMTRA decommissioning completed ●Groundwater remediation ongoing ●Long-term surveillance ongoing	●Tailings and contaminated materials (including demolition debris and windblown tailings) consolidated in disposal cell built during UMTRA	●6- to 12-inch riprap erosion protection layer ●6-inch granular bedding layer (capillary barrier) ●44-inch low permeability radon barrier layer (clayey soil)	Not reported	●"Measureable progress in removing contaminant mass from the aquifer is not accompanied by site wide decreases in contaminant concentrations. This suggests a prolonged period of active remediation, requiring the removal of multiple pore volumes from the contaminant plume." ●"Windblown sand continues to accumulate on the rock-covered surfaces, providing a favorable environment for plant growth."
	8	Mexican Hat Disposal Site		●UMTRA decommissioning completed ●Long-term surveillance ongoing	●3.6M cy of radioactive materials from tailings pile, demolished mill structures, 11 vicinity properties, and Monument Valley site consolidated in disposal cell built during UMTRA	●8- to 12-inch riprap erosion protection layer ●6-inch granular bedding layer (capillary barrier) ●24-inch low permeability radon barrier (material not specified)	Not reported	●Erosion of up gradient areas resulting in some sediment deposition in drainage channels
	9	Monument Valley Processing Site	April Gill (DOE)	●UMTRA decommissioning completed ●Groundwater remediation (natural attenuation) ongoing ●Evaluating using phytoremediation to expedite groundwater cleanup	●1M cy of residual source material and other site-related contamination removed and shipped to Mexican Hat disposal cell during UMTRA ●Sub-pile soils may be a continuing source of groundwater contamination (being evaluated as part of groundwater remedy)	N/A	Not reported	●Institutional controls to include fencing to prevent grazing by livestock and restrictions on use of groundwater during the remediation period (treated water being provided)
	10	United Nuclear Corporation Church Rock Mill (McKinley County, NM)		●OU1 - Groundwater remediation ongoing ●OU2 (new, created for relocation of mine waste from NECR mine) - Reclamation of tailings piles completed	●Windblown tailings excavated and placed in tailings piles ●Tailings piles regraded (coarse tailings on top of fine-grained tailings ●Tailings piles capped with interim radon barrier (soil/rock mulch cap) ●Drainage swales constructed on and around the reclaimed tailings piles	●6-inch soil/rock matrix ●6 inches of compacted soil ●12 inches of compacted soil (interim radon barrier)	Not reported	●Conflicting descriptions of cap components noted in site documents
	11	Tuba City Highway 160 Site	Cassandra Bleidel	●Site cleanup completed	●Excavated 6K cy of impacted soil and disposed off-site (Grand Junction, CO repository)	N/A	$5 million	●Soils disposed of offsite because waste originated at former Tuba City mill site and thus is classified as "residual radioactive material" (eligible for disposal at "stand-by" UMTRCA cell at Grand Junction) ●$5 million was for excavation and transport only, as no tipping fee applied in this case (disposal was "free")
Located Outside the Navajo Nation	12	San Mateo Mine (Cibola County, NM)	Steven McDonald (USFS) (505) 842-3838 smcdonald@fs.fed.us	●Soil removal action completed ●O&M ongoing (5 years)	●Excavation and consolidation of 136K cy of contaminated soil/waste rock on-site	●ET cap: - 18-inch admixture layer (2-inch to 3-inch rock blended with sandy loam) - 12-inch sandy loam layer - 12-inch clay loam layer	$7.2 million	
	13	Homestake Mining Company Superfund Site (Cibola County, NM)		●OU1 - Groundwater remediation ongoing ●OU2 - Interim stabilization of tailings piles, surface reclamation, and mill decommissioning completed ●OU3 - Radon mitigation at off-site properties completed	●Windblown tailings excavated and placed in larger of two tailings piles ●Radon barrier and "erosion-protection cover" constructed on sides of larger tailings pile (~21M tons), interim soil cover constructed on top ●Interim soil cover constructed on smaller tailings pile (~1.2M tons)	Not reported	Not reported	●Final radon barrier to be constructed on top of larger pile after tailings are dewatered ●Final radon barriers to be constructed on the smaller tailings pile once groundwater restoration is completed

Table 1: Summary of Clean-up Performed To Date at AUMs and Other Uranium-Related Sites In/Near the Navajo Nation

		Site	Contact Info	Status	Remedial Actions for Soil/Waste Rock/Tailings, etc.	Cap Details (if applicable)	Costs	Lessons Learned/Other Notes
Located Outside the Navajo Nation	14	Uravan Uranium Project Superfund Site (Montrose County, CO)		●Surface reclamation/remediation completed ●Groundwater remediation ongoing	●Capping and revegetating of 10M cubic yards of radioactive tailings on-site ●Excavation and consolidation of 530K cubic yards of raffinate crystals and contaminated soil on-site	●Tailings piles: - Riprap erosion protection layer - Granular bedding layer - Frost-protection layer (compacted soil) -Low permeability radon barrier layer (material not specified) ●Raffinate crystals: "earthen cover" topped by riprap (no further details)	$127 million	Cover specifications for tailings piles were not provided in site documentation reviewed by Roux Associates, but Fourth Five-Year Review Report for site (2010) states that the cover for the tailings piles was identical to the cover used for the Naturita Disposal Site repository (see below).
	15	Monticello Mill Tailings (USDOE) Superfund Site (San Juan County, UT)		●OU1/OU2 - Remediation of radioactively contaminated soils, mill tailings, and processing materials at mill site and contaminated soil and sediment at peripheral properties completed ●OU3 - Groundwater and surface water remediation ongoing	●Excavation and consolidation of 2.2M - 2.5M cy of contaminated soils, mill tailings, processing material, and sediment from mill site and peripheral properties/floodplain in off-site repository	●Cap: - 5.5-foot ET cap (w/gravel admixture in uppermost 8 inches and rock bio-barrier in lower part) - 12-inch sand-and-gravel capillary barrier - 60-mil HDPE geomembrane - 2-foot radon barrier (compacted soil) ●Liner: - 60-mil HDPE upper liner over geosynthetic clay liner - geonet (leak detection layer) - 60-mil HDPE lower liner over geosynthetic clay liner	Not reported	●Repository was designed to meet protective standards of 40 CFR 192.02 (radioactive materials) and to be functionally equivalent to a RCRA Subtitle C landfill ("double lined base and a lined, multi-layered cover system" with leachate detection and collection systems) because of other wastes encapsulated
	16	Ambrosia Lake Disposal Site (McKinley County, NM)		●UMTRA decommissioning completed ●Long-term surveillance ongoing	●All contaminated materials (6.9 million dry tons) consolidated in on-site disposal cell built during UMTRA	●6- to 12-inch riprap erosion protection layer ●6-inch granular bedding layer ●30-inch low permeability radon barrier layer (clayey soil)	Not reported	
	17	Slick Rock Processing and Disposal Sites (San Miguel County, CO)		●UMTRA decommissioning completed ●Groundwater remediation (natural attenuation) ongoing ●Long-term surveillance ongoing	●800K cy of tailings and other contaminated materials from two processing sites consolidated in off-site repository built during UMTRA	●8- to 12-inch riprap erosion protection layer ●6-inch granular bedding layer (capillary barrier) ●24-inch frost protection layer (compacted soil) ●18-inch low permeability radon barrier layer (clayey soil)	Not reported	
	18	Durango Processing and Disposal Sites (La Plata County, CO)		●UMTRA decommissioning completed ●Groundwater remediation (natural attenuation) ongoing ●Long-term surveillance ongoing	●2.5M cy of tailings, demolition debris, and contaminated materials from off-site properties consolidated in off-site repository built during UMTRA	●6-inch rock/soil matrix planted with grasses (top) or riprap erosion protection layer (side slopes) ●6-inch granular bedding layer (side slopes only) ●18- to 30-inch frost protection/rooting-medium layer (material not specified) ●18-inch rock bio-barrier (top only) ●6-inch sand filter/drainage layer (with bentonite mat on top only) ●24-inch low permeability radon barrier layer (material not specified)	Not reported	

Table 1: Summary of Clean-up Performed To Date at AUMs and Other Uranium-Related Sites In/Near the Navajo Nation

Site			Contact Info	Status	Remedial Actions for Soil/Waste Rock/Tailings, etc.	Cap Details (if applicable)	Costs	Lessons Learned/Other Notes
Located Outside the Navajo Nation	19	Naturirta Processing and Disposal Sites (Montrose County, CO)		●UMTRA decommissioning completed ●Long-term surveillance ongoing	●800K cy of contaminated soil and other contaminated material consolidated in off-site repository built during UMTRA	●12-inch riprap erosion protection layer ●6-inch granular bedding layer ●66-inch frost-protection layer (compacted soil) ●36-inch low permeability radon barrier layer (material not specified)	Not reported	●The disposal cell for the Naturita site is located at one end of a sandstone quarry and so is bounded on three sides be bedrock. Before contaminated materials were placed in the cell, clay was scraped from the floor of the quarry and used to line the bedrock walls of the cell
	20	Gunnison Processing and Disposal Sites (Gunnison County, CO)		●UMTRA decommissioning completed ●Groundwater remediation (natural attenuation) ongoing ●Long-term surveillance ongoing	●740K cy of tailings and other contaminated materials (including from off-site properties) consolidated in off-site repository built during UMTRA	●6-inch riprap erosion protection layer ●6-inch granular bedding layer (capillary barrier) ●72-inch frost-protection layer (compacted soil) ●6-inch granular bedding layer ●18-inch low permeability radon barrier layer (compacted clay amended with bentonite)	Not reported	
	21	Bluewater Disposal Site (Cibola County, NM)		●NRC reclamation completed ●Active groundwater terminated (alternative concentration limits adopted in lieu) ●Long-term surveillance ongoing	●23M+ tons of mill tailings, contaminated soils, demolished mill structures, and contaminated vicinity property materials (including non-uranium contamination) consolidated in seven on-site disposal cells (>90% of tailings in main tailings disposal cell)	●Main (acid) tailings disposal cell and smaller (basic) tailings disposal cell: - 4- to 12-inch riprap erosion protection layer - 1.7- to 2.6-foot low-permeability radon barrier layer (material not specified) ●Other cells (four): - soil/rock matrix or topsoil, seeded with native grasses - radon barrier layer (material not specified)	Not reported	●There is also a disposal cell for PCB-contaminated radioactive material. The material is sealed in drums, with all void space filled with a soil-cement mixture. The spaces between the drums are also filled with a soil-cement mixture. The drums are covered on all sides (top, bottom, sides) with a 3-foot-thick clay liner. The entire cell was then covered with a radon barrier and a layer of riprap
	22	L-Bar Disposal Site (Cibola County, NM)		●NRC reclamation completed ●Active groundwater terminated (alternative concentration limits adopted in lieu) ●Long-term surveillance ongoing	●All tailings and other contaminated materials (2.1 million tons) consolidated in on-site disposal cell	●2- to 6-foot soil cover (riprap on side slopes) ●4.1-foot low-permeability radon barrier layer (compacted clay)	Not reported	●The cap design assumed the soil cover would "reestablish with local vegetation"

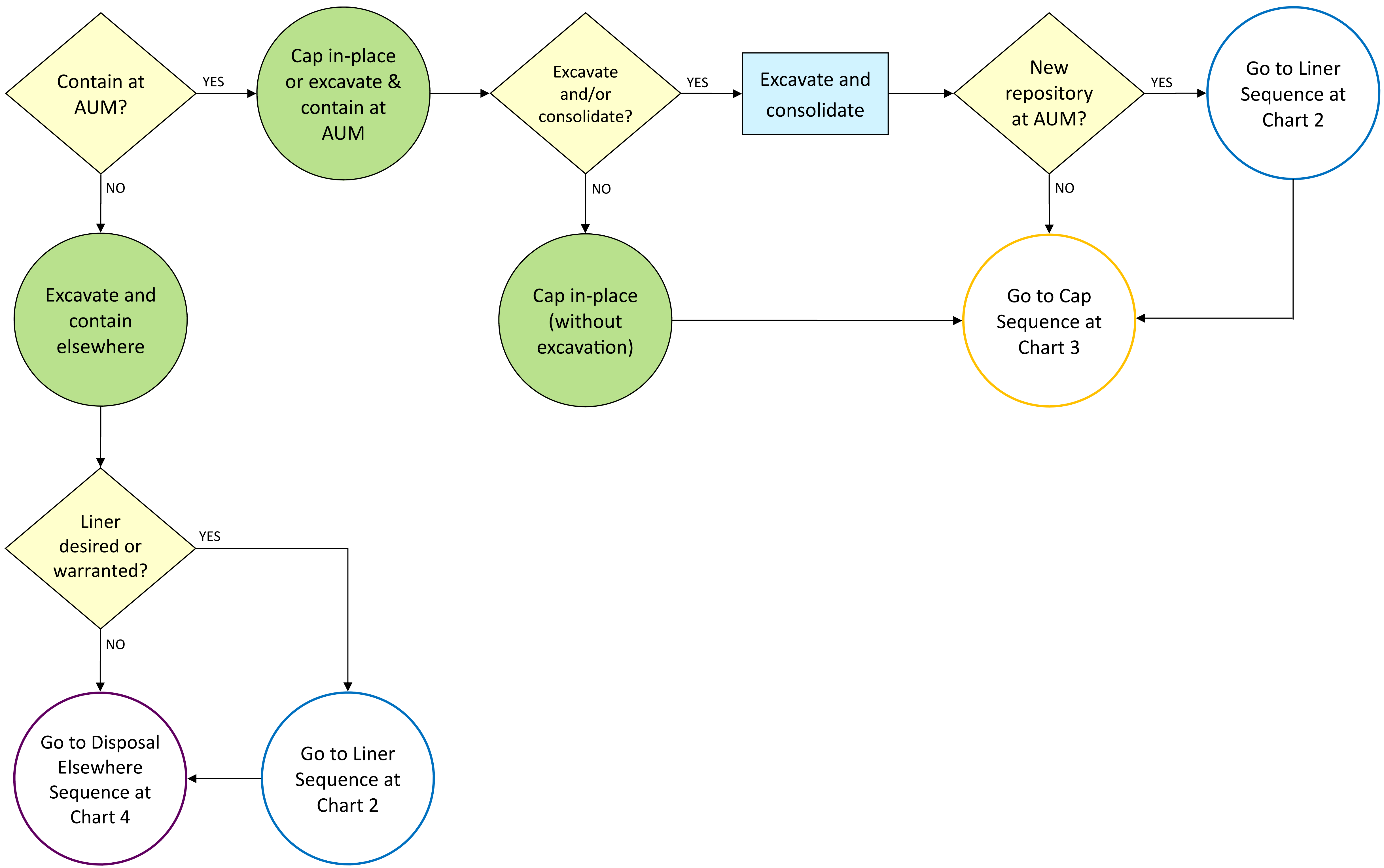
Table 2: Screeneing Criteria for AUM Waste Clean-up Alternatives

AUM Characteristics and Other Considerations*	Remedial Alternatives							
	Alternative 1: Cap the AUM waste in-place at the AUM	Alternative 2: Excavate and consolidate the AUM waste and contain it at the AUM	Alternative 3: Excavate and consolidate the AUM waste and contain it in a new repository	Alternative 4: Excavate and consolidate the AUM waste and contain it at a nearby AUM	Alternative 5: Excavate and consolidate the AUM waste and contain it in a: Local Repository	Alternative 5: Regional Repository	Alternative 5: Central Repository	Alternative 6: Excavate the AUM waste and dispose of it outside the Navajo Nation
No residents within 1/4 mile of AUM	✓	✓	✓					No limiting factors
No surface water within 1/4 mile of AUM	✓	✓	✓					
Groundwater within 1 mile of AUM not used for drinking water and/or livestock watering	✓	✓	✓					
Relatively easy to access (for periodic inspections/monitoring)	✓	✓	✓					
Roads adequate for repeated heavy vehicle access (for ongoing maintenance as needed)	✓	✓	✓					
Terrain supports cap constructability	✓	✓	✓					
Climatological conditions (freeze/thaw cycles, higher precipitation) won't increase cost for cap construction beyond cost to transport waste elsewhere	✓	✓	✓					
Liner not desired/warranted	✓	✓						
Waste limited to discrete pile(s)	✓							
Adequate space at AUM for repository (limited excavation required to build)			✓					
AUM amenable to on-site containment located nearby				✓				
Suitable location for repository nearby					✓			
Suitable location for repository within AUM region						✓		
Suitable centralized location for repository available within Navajo Nation							✓	

* The specific circumstances (decision factors) by which an alternative is selected within these flow charts has not been fully vetted with Navajo EPA or the USEPA. Further, a detailed alternatives screening pursuant to the federal and Navajo NCP will be required based upon AUM specific conditions.

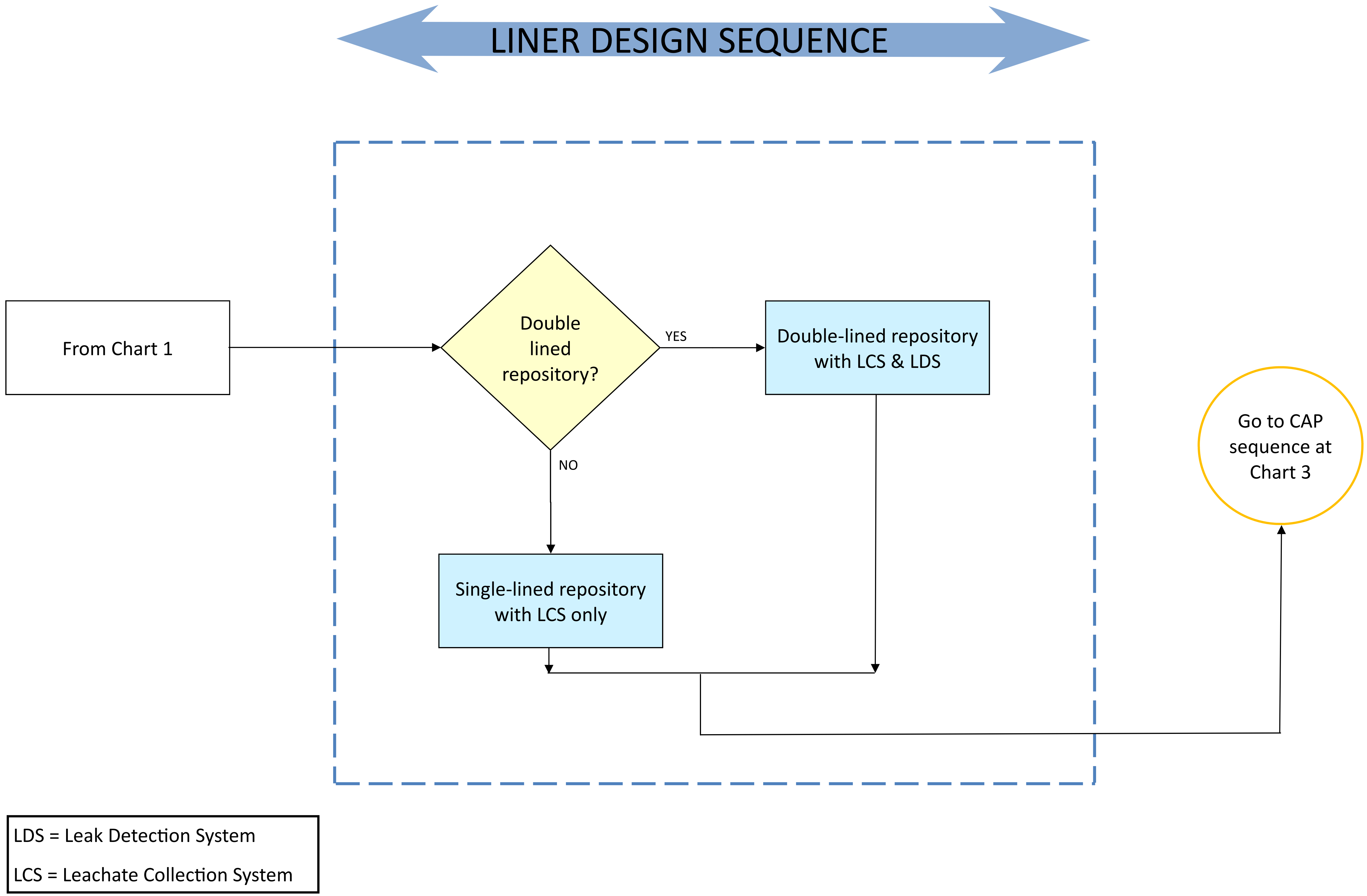
CHARTS

Chart 1: AUM Cleanup-Contain at AUM or Elsewhere



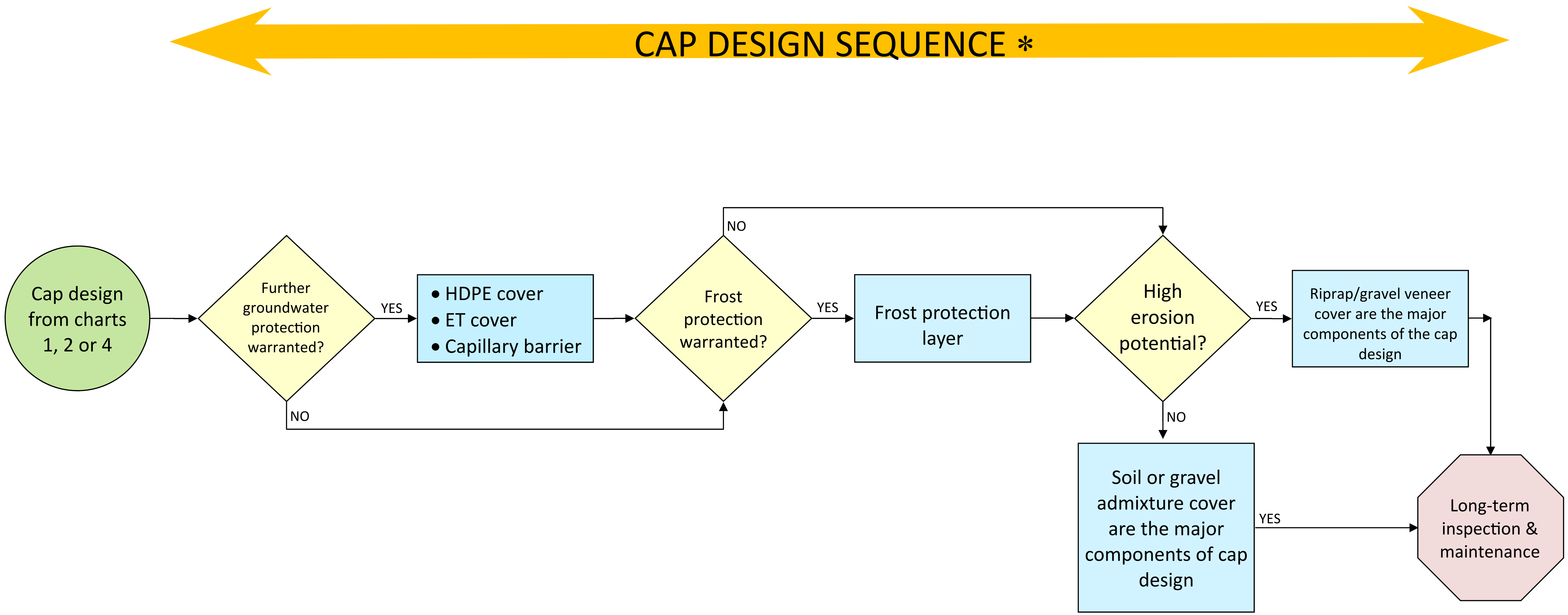
2282.0001M000.102/C1-4

Chart 2: Liner Design Sequence



2282.0001M000.102/C1-4

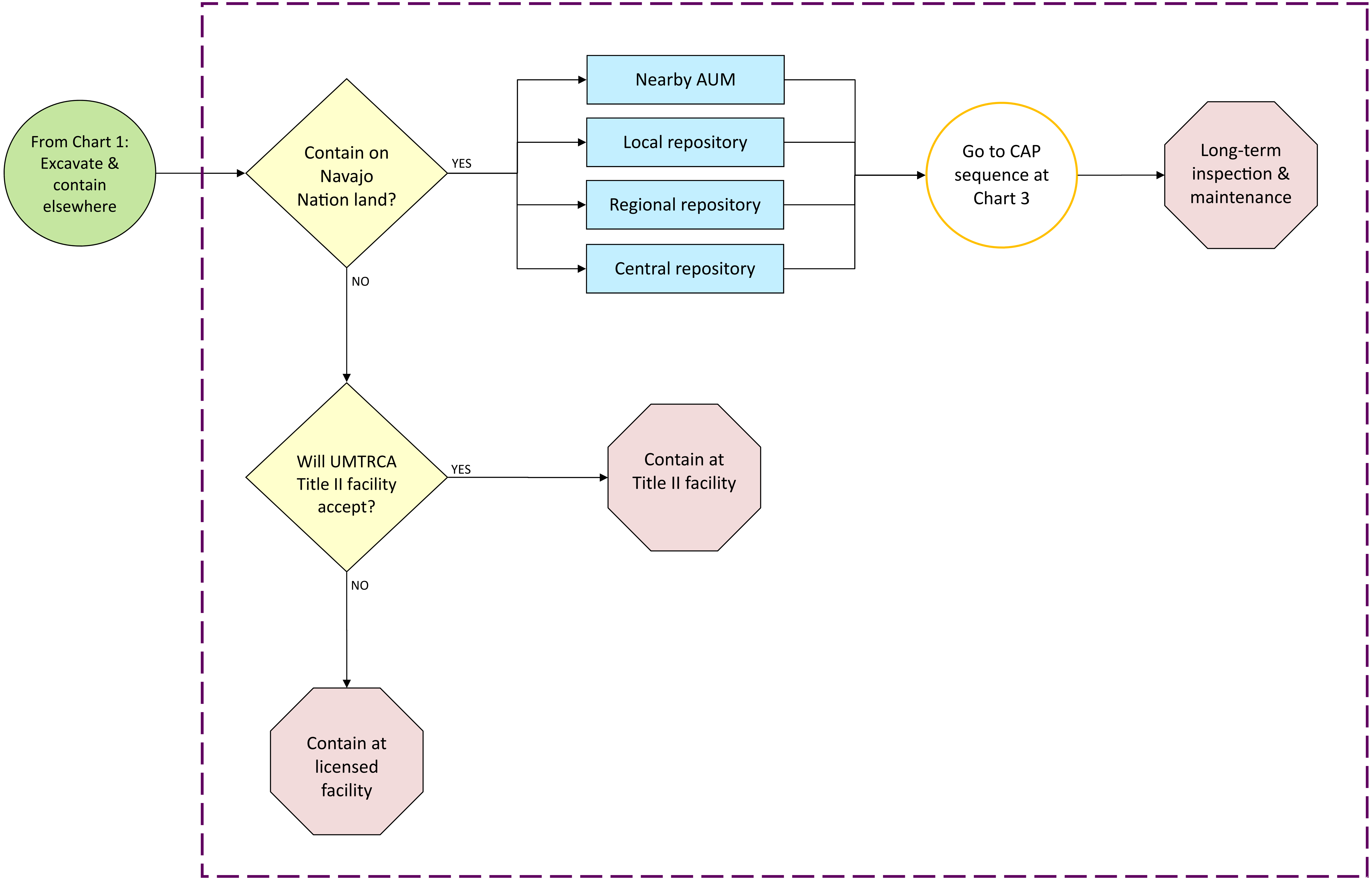
Chart 3: Capping Design Sequence



HDPE = High density polyethylene
ET = Evapotranspiration
* All covers will include a radiation barrier which may be provided by one or more of the protective layers

2282.0001M000.102/C1-4

Chart 4: Disposal Elsewhere Sequence



2282.0001M000.102/C1-4

APPENDICES

APPENDIX A

Tables Summarizing Physical and Chemical Properties of Select Radiological Compounds and Analytical Methods for their Detection

Appendix A:

Tables Summarizing Physical and Chemical Properties of Select Radiological Compounds and Analytical Methods for their Detection

Physical Properties of Radium (from ATSDR)[1]

TABLE 3-2. Physical and Chemical Properties of Selected Radium Compounds[a]

Property	Radium	Radium Bromide	Radium Carbonate	Radium Chloride	Radium Hydroxide	Radium Iodate	Radium Nitrate	Radium Sulfate
Chemical formula	Ra	$RaBr_2$	$RaCO_3$	$RaCl_2$	$Ra(OH)_2$	$RaIO_3$	$RaNO_3$	$RaSO_4$
Molecular weight	226.03	385.83	286.03	296.93	No data	575.83	350.04	382.08
Synonyms	No data	No data	Carbonic acid, radium salt	No data	No data	No data	Nitric acid, radium salt	Sulfuric acid, radium salt
CAS number	7440-14-4	10031-23-9	7116-98-5	10025-66-8	98966-86-0	No data	10213-12-4	7446-16-4
Color	Silver-white	White	White	Yellowish-white	No data	No data	No data	White
Physical state	Solid	Solid	Solid	Solid	No data	No data	Solid	Solid
Melting point	700°C	728°C	No data	1000°C	No data	No data	No data	No data
Boiling point	<1140°C	900°C (sublimes)	No data	No data	No data	No data	No data	No data
Density at 20°C	5	5.79	No data	4.91	No data	No data	No data	No data
Odor	No data	No data	No data	No data	No data	No data	No data	No data
Odor threshold:								
Water	No data	No data	No data	No data	No data	No data	No data	No data
Air	No data	No data	No data	No data	No data	No data	No data	No data
Solubility:								
Water at 20°C	Decays	Soluble	Insoluble	Soluble	No data	Soluble	Soluble	Insoluble
Other solvents	Decays in acids	Soluble in alcohol	Decomposes in acids	Soluble in alcohol	No data	No data	No data	Insoluble in acids
Partition coefficients:								
Log octanol/water	NA[b]	NA	NA	NA	NA	NA	NA	NA
Log K_{oc}	NA	NA	NA	NA	NA	NA	NA	NA
Vapor pressure at 20°C	No data	No data	No data	No data	No data	No data	No data	No data
Henry's law constant:	NA	NA	NA	NA	NA	NA	NA	NA
Autoignition temperature	No data	No data	No data	No data	No data	No data	No data	No data
Flashpoint	No data	No data	No data	No data	No data	No data	No data	No data
Flammability limits	No data	No data	No data	No data	No data	No data	No data	No data
Conversion factors	No data	No data	No data	No data	No data	No data	No data	No data

[a]Sources: CHEMNAME 1989; Sax and Lewis 1987; Weast 1985; Windholz 1983.
[b]NA = not applicable

[1] ATSDR for Radon: http://www.atsdr.cdc.gov/toxprofiles/tp144.pdf

Physical Properties of Uranium Compounds (from ATSDR)[2]

Table 4-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Uranium hexafluoride	Uranium tetrachloride	Uranyl fluoride[c]	Uranyl acetate, dihydrate	Uranyl nitrate hexahydrate
Atomic/molecular weight	352.019	379.841	308.0245	424.146	502.129
Chemical formula	UF_6	UCl_4	UO_2F_2	$UO_2(CH_3COO)_2 \cdot 2H_2O$	$UO_2(NO_3)_2 \cdot 6H_2O$
Synonyms	Uranium(VI) fluoride	Uranium (IV) chloride	Uranium oxyfluoride; uranium fluoride oxide	bis(Acetate-B) dioxouranium	bis(Nitrate-O) dioxouranium; hexahydrate
Common names	No data	Green salt	No data	No data	No data
CAS Registry No.	7783-81-5	10026-10-5	13536-84-0[a]	6159-44-0	13520-83-7
Color	White crystalline[a]	Green	Yellow[a]	Yellow	Yellow
Physical state	Solid[a]	Octahedral crystal	Solid[a]	Solid crystal	Solid crystal
Odor	No data	No data	No data	No data	No data
Melting point, °C	64.5 at 2 atm[a]	590°C	Decomposes at 300	Loses $2H_2O$ at 110	60
Boiling point, °C	56.2 sublimation point[a]	791	Not relevant	Decomposes at 275	Decomposes at 118
Autoignition temperature	No data	No data	No data	No data	No data
Solubility:					
Water	Reacts with H_2O	Reacts with water	64.4 g/100 g at 20 °C	7.7 g/100 mL at 15 °C	127 g/100 gH_2O
Other solvents	Soluble in CCl_4, TCE, and chloroform[a]	Soluble in ethanol	Soluble in ethanol and benzene[a]	Soluble in ethanol	Soluble in ethanol and ether
Density g/cm^3	5.09 at 20.7°C; 3.595 at 70°C	4.72	6.37	2.893 g/cm^3 at 15°C	2.81 g/cm^3 at 13°C
Partition coefficients	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Vapor pressure	115 mmHg at 25°C [c]	No data	No data	No data	No data
Henry's law constant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Refractive index	No data	No data	No data	No data	1.4967
Flashpoint	No data	No data	No data	No data	No data
Flammability limits	No data	No data	No data	No data	No data
Conversion factor[b]	1 µg=0.47 pCi	1 µg=0.43 pCi	1 µg=0.53 pCi	1 µg=0.39 pCi	1 µg=0.33 pCi

2 ATSDR for Uranium: http://www.atsdr.cdc.gov/toxprofiles/tp150.pdf

Table 4-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Uranyl nitrate (not hexahydrate)	Ammonium diuranate	Uranium peroxide	Uranyl acetate
Atomic/molecular weight	394.037	624.131	302.03[a]	388.12[a]
Chemical formula	$(UO_2)(NO_3)_2$	$(NH_4)_2U_2O_7$	UO_4[a]	$C_4H_6O_6U$[a]
Synonyms	No data	Ammonium uranate(VI)	No data	No data
Common names	No data	No data	No data	No data
CAS Registry No.	10102-06-4	7783-22-4	19525-15-6[a]	541-09-3[a]
Color	Yellow	Reddish yellow	Pale yellow[a]	Yellow[a]
Physical state	Solid crystal	Amorphous powder	Solid	Solid crystals[a]
Odor	No data	No data	No data	Vinegar-like[a]
Melting point, °C	No data	No data	Decomposes at 90–195°C [a]	No data
Boiling point, °C	No data	No data	No data	Decomposes at <275[a]
Autoignition temperature	Not relevant	Not relevant	Not relevant	Not relevant
Solubility:				
Water	127 g/100 g H_2O	Insoluble	0.0006 g/100 cc at 20°C; 0.008 g/cc at 90°C [a]	7.694/100 mL at 15°C[a]
Other solvents	Soluble in ether	Insoluble in alkali; soluble in acids	No data	Very soluble in alcohol[a]
Density g/cm^3	No data	No data	11.66 (calculated)[a]	2.893 at 15°C[a]
Partition coefficients	No data	No data	No data	No data
Vapor pressure	No data	No data	No data	No data
Henry's law constant	No data	No data	No data	No data
Refractive index	No data	No data	No data	No data
Flashpoint	No data	No data	No data	No data
Flammability limits	No data	No data	No data	No data
Conversion factor[b]	1 μg ≡ 0.42 pCi	1 μg ≡ 0.52 pCi	1 μg ≡ 0.54 pCi	1 μg ≡ 0.42 pCi

[a]HSDB (2011).
[b]Calculated from National Nuclear Data Center data (NNDC 2011).
[c]Argonne National Laboratory (2011).

Source: Lide (2008), unless annotated

Physical Properties of Radon (from ATSDR)[3]

Property	Radon
Molecular weight	222 (radon), 220 (thoron), 219 (actinon)
Color	Colorless
Physical state	Gas at 0 °C and 760 mm Hg
Melting point	-71 °C
Boiling point	-61.8 °C
Density at -20 °C	9.96×10^{-3} g/cm^3
Odor[b]	Odorless
Odor threshold:	
Water	Odorless
Air	Odorless
Solubility:	
Water at 20 °C	230 cm^3/L
Organic solvents	Organic liquid, slightly soluble in alcohol
Vapor pressure at 25 °C[a]	395.2 mm Hg
Henry's Law constant	No data
Autoignition temperature	Noble gas; does not autoignite
Flash point	Noble gas; does not burn
Flammability limits	Noble gas; is not flammable
Half-life:	
^{222}Rn	3.8235 days
^{220}Rn	55.6 seconds
^{219}Rn	3.96 seconds
Decay energies (MeV), and intensities (%)	
^{222}Rn	Alpha particles: 4.826 (0.0005%) 4.986 (0.078%) 5.48948 (99.920%) Gamma rays: 0.510 (0.076%)
^{220}Rn	Alpha particles: 5.747 (0.114%) 6.288 (99.886%) Gamma rays: 0.5497 (0.114%)

3 ATSDR for Radon: http://www.atsdr.cdc.gov/toxprofiles/tp145.pdf

Property	Radon
^{219}Rn	Alpha particles (15 reported): 6.425 (7.5%) 6.530 (0.12%) 6.553 (12.9%) 6.819 (79.4%) Gamma rays (dozens reported): 0.0111 (9.6% 0.0769 (5.0%) 0.0793 (8.4%) 0.2712 (10.8%)
Specific activity, nλ/mass (Ci/g):	
^{222}Rn	$1.538x10^5$
^{220}Rn	$9.135x10^8$
^{219}Rn	$1.301x10^{10}$
Decay products:	Radon progeny (daughters)
^{222}Rn (see Figure 4-1)	^{218}Po ^{214}Pb ^{214}Bi ^{214}Po ^{210}Tl ^{210}Pb ^{210}Bi ^{210}Po ^{206}Tl ^{206}Pb
^{220}Rn (see Figure 4-2)	^{216}Po ^{212}Pb ^{212}Bi ^{212}Po ^{208}Tl ^{208}Pb
^{219}Rn (see Figure 4-3)	^{215}Po ^{215}At ^{211}Pb ^{211}Bi ^{211}Po ^{207}Tl ^{207}Pb

MeV = million electron volts

Table 7-2 Analytical Methods for Determining Uranium in Environmental Samples[4]

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Air	Air particulate collection on glass fiber filter; digestion in HNO_3	ICP-MS (total uranium)	0.1 µg/L in final solution	No data	Boomer and Powell 1987
Air	Spiked air particulate dry and wet ashed; dissolution; coprecipitation with iron hydroxide and Ca oxalate, purification by solvent extraction and electrodeposition onto platinum	α-Spectrometry (isotope quantification)	0.02 dpm/L[b] for ^{238}U in solution	No data	Singh and Wrenn 1988
Air	Sample collection on cellulose filters; ashing; extraction with triisooctylamine; purification by anion exchange chromatography and coprecipitation.	α-Spectroscopy	0.015 pCi	No data	EPA 1984b
Air	Collection on cellulose filters	INAA	0.03 µg per filter	No data	Querol et al. 1997
Rainwater	Coprecipitation with iron hydroxide, radiochemical, ion-exchange and solvent extractive purification, and electrodeposition on steel	α-Spectrometry (isotope quantification)	0.02 dpm/L for ^{238}U in solution[a]	68%	Jiang et al. 1986

4 Keith S, Faroon O, Roney N, Et Al. "Toxicological Profile for Uranium. Atlanta (GA): Agency for Toxic Substances and Disease Registry; February 2013: http://www.ncbi.nlm.nih.gov/books/NBK158797/table/T32/?report=objectonly

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Drinking water	Direct analysis or concentration by co-precipitation and solvent extraction; fusion	Fluorometry (total uranium)	<20 µg/L (direct); 0.1 µg/L (cleaned)	104% (cleaned)	EPA 1980c (EPA Method 908.1)
Drinking water	Concentrated by co-precipitation; separation; clean-up by ion-exchange	Gross α-counting (total uranium)	1 pCi/L	92.6%	EPA 1980c (EPA Method 908.0)
Drinking water	Sample chelation in EDTA; addition of Fluron	Laser-induced fluorometry	0.08 µg/L	100% at 1 µg/L	EPA 1984e (EPA Method 908.2)
Natural waters	Sample concentration by cation-exchange resin, separation by ion-exchange resin and complexation with Arsenazo III	Spectro-photometry (total uranium)	0.1 µg/L	80%	Paunescu 1986
Water	Sample fusion with NaF and LiF	Fluorometry (total uranium)	5 µg/L	117.5% at 6.3 µg/L	ASTM 1986 (ASTM Method D2907-83)
Water	Coprecipitation with iron hydroxide; purification by ion-exchange chromatography and electrodeposition	α-Spectrometry (isotope quantification)	0.02 dpm/L	97.7–108% at 0.028–0.044 Bq/L	ASTM 1986 (EPA Method D3972-82)
Water	Solvent extraction; coprecipitation with $BaSO_4$; dissolution in $HClO_4$; reprecipitation with TiF_3; filtration	α-Spectrometry (isotope quantification)	0.02 dpm/L[b] for ^{238}U	No data	Stewart et al. 1988

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Water	Preconcentration by complexation with oxine and adsorption on activated carbon	NAA (total uranium)	3 μg/L	>80%	Holzbecher and Ryan 1980
Water	Preconcentration by ion-exchange chromatography; purification by ion-exchange and solvent extraction	NAA (^{235}U and ^{238}U)	No data	No data	Gladney et al. 1983
Water	Extraction by ion-exchange; dissolution in low oxygen solvent; irradiation	Delayed neutron analysis (total uranium)	0.4 μg/L	No data	Zielinski and McKown 1984
Water	Wet-ashed; reaction with complexant	Pulsed-laser phosphorimetry	0.05 ppb	103% (average)	ASTM 1994 (Method 5174-91)
Water (uranyl nitrate)	Solvent extraction	Fluorescence spectroscopy	6.1–10.5 ppm	No data	ASTM 1994 (Method D4763-88)
Ground-water	Separation on resin; automated	FI-ICP-MS (isotope quantification)	0.3 ng/L for ^{238}U	±1.8%	Aldstadt et al. 1996
Ground-water	Separation and concentration on two HPLC columns; complexation with Arsenazo III	Spectro-photometry (total uranium)	1–2 μg/L	No data	Kerr et al. 1988
Water and wastes	Acid digestion; filtration (dissolved); acid digestion (total recoverable)	ICP-MS (total uranium)	0.1 μg/L	105–110%	EPA 1991a (EPA Method 200.8)

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Seawater	Uranium enriched by chelation with APDC in the presence of Fe^{+2}, complexation with APDC followed by adsorption on activated carbon	X-ray fluorescence (total uranium)	0.56–0.64 µg/L	No data	Nagj et al. 1986
Seawater	Oxine addition	Cathodic stripping voltametry (total uranium)	0.02–0.2 nM	No data	Van den Berg and Nimmo 1987
Sediment	Sediment dried and well-mixed; dissolution in HCl-$HClO_4$-HF; purification by coprecipitation, ion exchange and electrodeposition	α-Spectrometry (isotope quantification)	No data	No data	Anderson and Fleer 1982
Soil	Soil leached with HCl-HNO_3-HF; purification by ion-exchange, and solvent extraction, and electrodeposition	α-Spectrometry (isotope quantification)	No data	No data	Golchert et al. 1980
Soil	Dissolution in HCl-HNO_3-HF; purification by coprecipitation, solvent extraction and electrodeposition	α-Spectrometry (isotope quantification)	0.03 µg/sample	67%	Singh and Wrenn 1988
Soil, sediment, and biota	Ashing; fusion with KF and $K_2S_2O_7$; purification by extraction with triisooctylamine, anion exchange chromatography and coprecipitation.	α-Spectroscopy	No data	No data	EPA 1984b

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Soil, sediment, and biota	Ashing; extraction into triisooctylamine, strip from triisooctylamine with HNO_3 and coprecipitation with lanthanum.	gross α-Spectroscopy or α-spectroscopy	No data	No data	EPA 1984b
Minerals	Dissolution in HNO_3-HF-$HClO_4$; purification by solvent extraction	Laser fluorometry (total uranium)	No data	No data	Veselsky et al. 1988
Low level radioactive waste	Dissolution; purification by coprecipitation, ion-exchange and electrodeposition	α-Spectrometry (isotope quantification)	0.03 dpm	No data	Wessman 1984
Building materials and lichen	Wet ashing with HNO_3-H_2O-HF; purification by coprecipitation, solvent extraction and electrodeposition	α-Spectrometry (isotope quantification)	0.03 µg/sample	54–73%	Singh and Wrenn 1988
Vegetation	Sample dried and homogenized; dry and wet ashing	ICP-MS (total uranium)	0.1 µg/L in final solution	No data	Boomer and Powell 1987
Vegetation	Sample dried and homogenized; wet ashing and purification by solvent extraction	Laser fluorometry (total uranium)	0.05 mg/kg in plant ash	No data	Harms et al. 1981
Process water	Dilution and filtration water	Laser fluorometry (total soluble uranium)	0.01 µg/L[b]	No data	Hinton and White 1981
Process water	Direct analysis	Ion chromatography spectrophotometric detection ($U^{+}6$)	0.04 mg/L	No data	Byerley et al. 1987

Sample matrix	Sample preparation	Analytical method	Sample detection limit	Accuracy	Reference
Field survey	None	Scintillation detector and count rate meter	200–500 dpm/100 cm^2 (scintillation detector)	No data	ANSI 1978 (ANSI Standard N323)

A: This detection limit was reported by Melgard 1988.

B: This detection limit was reported by Wessman 1984.

APDC = ammonium pyrrolidine dithiocarbamate; Bq = Bequerel and 1 pCi = 0.37 Bq; dpm = disintegration per minute and 1 pCi = 2.22 dpm; EDTA = ethylenediaminetetraacetic acid; FI = flow injection; HPLC = high performance liquid chromatography; ICP = inductively coupled plasma spectrometry; INAA = instrumental neutron activation and analysis; MS = mass spectrometry; NAA = neutron activation analysis; nM = nanomole or 10^{-9} of a mol

USEPA Approved Drinking Water Methods for Radium-226[5]

Table 5 Approved Methods - Radium-226

Method	Reference	Methodology	Minimum Detectable Level[a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
1- Method 903.1	EPA 1980	Radon emanation; count alpha by scintillation counter.	0.5	1,000	100	There are no radioactive interferences in this method. The calibration constant of each scintillation cell must be determined using a standardized radium-226 solution.
2	EPA 1976	Radon emanation; count alpha by scintillation counter.	0.01-0.04	1,000	1,000-60	The calibration constant is determined using radium-226 standard solution.
3 - Method Ra-04	EPA 1984	Radon emanation; count alpha by scintillation counter.	na[b]	na	na	The calibration constant is determined by sealing a known quantity of radium-226 in a de-emanation tube.
4	EPA 1979	Radon emanation (for radium-226); for radium-226, count alpha by scintillation counter and for radium-228, count beta by low-level proportional counter.	0.3	1,500	na	This method is applicable for the determination of radium-226 and radium-228 in water, soil, air, biological tissues, and biological fluids.
5 - Method 7500-Ra C	APHA 1995	Radon emanation; count alpha by scintillation counter.	0.03-0.05	1,000	na	This method is suitable for the determination of soluble, suspended, and total radium-226.
6 - Method 305	APHA 1971	Radon emanation; count alpha by scintillation counter.	0.03-0.05	1,000	na	This method requires a moderate amount of chemistry coupled with a sensitive alpha scintillation count of radon-222 plus progeny in a small chamber.
7 - Method D 3454-91	ASTM 1994	Radon emanation; count alpha by scintillation counter.	0.1	na	na	This method covers the measurement of soluble, suspended, and total radium-226 in water.
8- Method R-1141-76	GSI 1977	Radon emanation; count alpha by scintillation counter.	0.1	1,000	1,000	This method is applicable to any water sample.

5 Compendium of EPA Approved Analytical Methods for Measuring Radionuclides in Drinking Water, June 1998: https://www.orau.org/ptp/PTP%20Library/library/DOE/Misc/radmeth3.pdf

Method	Reference	Methodology	Minimum Detectable Level[a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
9- Method Ra-05	DOE 1990	Radon emanation; count alpha by ionization chamber or scintillation cell.	na	na	na	Only radium-226 yields radon-222 progeny that has suitable characteristics for detection by an emanation technique; therefore, the procedure is specific.
10- Method Ra-02	RSI 1982	Radon emanation (for radium-226); count alpha by scintillation cell for radium-226 and by beta/gamma coincidence counter for radium-228.	na	na	na	This method is applicable to water, soil, and air particulate samples and can be used to measure radium-226 alone or radium-226 in conjunction with radium-228.
11- Method 903.0	EPA 1980	Radiochemical/precipitation; counted by alpha scintillation or gas-flow proportional alpha particle counting.	0.5	1,000	100	The method does not always give an accurate measurement of the radium-226 content of the sample (when other radium alpha emitters are present); it can be used to screen samples. Absolute measurement can be made by calibrating the alpha detector with standard radium-226 in the geometry obtained with the final precipitate
12	EPA 1976	Radiochemical/precipitation; count alpha by internal proportional counter.	0.4-0.15	2,000	1,000-60	None.
13- Method Ra-03	EPA 1984	Radiochemical/precipitation; alpha counting by scintillator counter.	na	na	na	Radium-226 in solution is determined by coprecipitation from the sample with barium sulphate. The sample is then analyzed using the de-emanation procedure
14- Method 7500-Ra B	APHA 1995	Radiochemical/precipitation; alpha counting by gas-flow proportional counter, scintillation counter, or thin end-window gas-flow proportional counter.	na	na	na	This method is suitable for determination of the alpha-emitting isotopes of radium.
15- Method 304	APHA 1971	Radiochemical/precipitation; alpha counting by gas-flow internal proportional counter, scintillation counter, or thin end-window gas-flow proportional counter.	na	na	na	This method is designed to measure radium in clear water. It is applicable to sewage and industrial wastes, provided steps are taken to destroy organic matter and eliminate other interfering ions.

Method	Reference	Methodology	Minimum Detectable Level[a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
16- Method D 2460-90	ASTM 1994	Radiochemical/precipitation; alpha counting by gas-flow counter or scintillation counter.	1.0	na	na	This method covers the separation of dissolved radium from water for the purpose of measuring its radioactivity.
[1] 17- Method R-1140-76	GSI 1977	Radiochemical/precipitation; alpha counting by low-background, anticoincidence, thin window, gas proportional counter.	1.0	1,000	100	This method is satisfactory for applications that do not require high precision or radium isotope identification.

[a] Minimum detectable level is defined as the minimum detectable concentration reported for the method at the 99% confidence level (EPA 1980) or at the 95% confidence level (EPA 1976).
[b] na - information not available.

USEPA Approved Drinking Water Methods for Radium-228[6]

Table 6 Approved Methods - Radium-228

Method	Reference	Methodology	Minimum Detectable Level[a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
1- Method 904.0	EPA 1980	Radiochemical/precipitation; count by gas-flow proportional beta counter.	1.0	1,000	100	This technique is devised so that the beta activity from actinium-228, which is produced by decay of radium-228, can be determined and related to the radium-228 that is present in the sample.
2	EPA 1976	Radiochemical/precipitation; beta counting for actinium-228 to get radium-228 reading and alpha internal proportional counting for radium-226.	0.06-0.3	2,000	1,000-60	In this method, if after sufficient beta decay of the actinium fraction, it is determined that there is no radium-228 in the sample, then the radium-226 fraction may be alpha counted directly. If radium-228 is present, then the radium-226 must be determined by radon emanation.
3 - Method Ra-05	EPA 1984	Radiochemical precipitation; count for beta in a low background proportional counter.	na[b]	na	na	The sample may be taken from the stored solution following radium-226 de-emanation or from a water sample.
4	EPA 1979	Radon emanation (for radium-226) followed by radiochemical/precipitation (for radium-228); for radium-226, count alpha by scintillation counter and for radium-228, count beta by low-level proportional counter.	0.3	1,500	na	This method is applicable for the determination of radium-226 and radium-228 in water, soil, air, biological tissues, and biological fluids.
5 - Method 7500 Ra D	APHA 1995	Radiochemical/precipitation; count for radium-228 by gas-flow internal proportional counter or thin end-window gas-flow proportional counter. For radium-226, count by scintillation counter.	na	na	na	This method can be used to determine soluble radium-228 alone or soluble radium-228 plus radium-226.
6 - Method R-1142-76	GSI 1977	Radiochemical/precipitation; beta counting by low-background, anticoincidence, thin window, gas proportional counter.	1.0	4,000-1,000	300-500	This method is applicable to all natural water samples. No chemical interferences have been detected.
7- Method Ra-02	RSI 1982	Radon emanation (for radium-226) followed by radiochemical/precipitation (for radium-228); count alpha by scintillation cell for radium-226 and by beta/gamma coincidence counter for radium-228.	na	na	na	This method is applicable to water, soil, and air particulate samples and can be used to measure radium-226 alone or radium-226 in conjunction with radium-228.
8	DEP 1980	Radiochemical/precipitation; count by low-background beta counter.	0.4	1,000	100	Each laboratory that uses this method is required to operate a formal quality control program.

[a] Minimum detectable level is defined as the minimum detectable concentration reported for the method at the 99% confidence level (EPA 1980) or at the 95% confidence level (EPA 1976).

[b] na - information not available.

[6] Compendium of EPA Approved Analytical Methods for Measuring Radionuclides in Drinking Water, June 1998: https://www.orau.org/ptp/PTP%20Library/library/DOE/Misc/radmeth3.pdf

USEPA Approved Drinking Water Methods for Uranium[7]

Table 7 Approved Methods - Uranium

Method	Reference	Methodology	Minimum Detectable Level [a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
1- Method 908.0	EPA 1980	Radiochemical/precipitation; count for alpha particle activity by gas-flow proportional or scintillation counting.	1.0	1,000	100	This method covers the measurement of total uranium alpha particle activity in drinking water.
2- Method 7500-U B	APHA 1995	Radiochemical/precipitation; count by gas-flow proportional counter or alpha scintillation counting.	na[b]	na	na	This method determines total alpha activity without making an isotopic uranium analysis.
3- Method 908.1	EPA 1980	Direct fusion or fusion after extraction; count by fluorometer.	1.0	1,000	100	This method covers the determination of soluble uranium in waters at concentrations greater than 0.1 µg/L.
4- Method 7500-U C	APHA 1989	Direct fusion or fusion after extraction; count by fluorometer.	na	na	na	For samples containing > 20 µg/L U, uranium is determined directly. For samples containing < 20 µg/L U, uranium is first separated from quenching elements and excessive salt concentrations.
5- Method D 2907-91	ASTM 1994	Direct fusion or fusion after extraction; count by fluorometer.	5 µg/L	na	na	This test method is applicable to the determination of micro quantities of uranium in water.
6- Method R-1180-76	GSI 1977	Direct fusion; count by fluorometer.	0.3 µg/L	na	na	This method is suitable for determination of uranium in nonsaline water in which uranium fluorescence is quenched less than 30%.
7 - Method R-1181-76	GSI 1977	Extraction and fusion; count by fluorometer.	0.01 µ g/L	na	na	This method is applied to water samples where the reduction of uranium fluorescence by quenching exceeds 30%.
8- Method U-04	DOE 1990	Extraction and fusion; count by fluorometer.	na	na	na	This procedure has been used to analyze bone, soil, food, tissue, air filter, and water samples.

7 Compendium of EPA Approved Analytical Methods for Measuring Radionuclides in Drinking Water, June 1998: https://www.orau.org/ptp/PTP%20Library/library/DOE/Misc/radmeth3.pdf

Method	Reference	Methodology	Minimum Detectable Level [a] (pCi/L)	Sample Size (mL)	Counting Time (min)	Noteworthy Features
9- Method 00-07	EPA 1984	Radiochemical separation, electrodeposition on stainless steel disk; count by alpha spectrometer.	na	na	na	None.
10	EPA 1979	Radiochemical separation, electrodeposition on stainless steel disk; count by alpha spectrometer.	0.02	na	na	This method is appropriate for the analysis of isotopic plutonium, uranium, and thorium, collectively or individually.
11- Method 7500-U C	APHA 1995	Radiochemical separation, electrodeposition on stainless steel disk; count by alpha spectrometer.	0.1	na	na	This method determines the isotopic content of the uranium activity; it is consistent with determining the differences among naturally occurring, depleted, and enriched uranium.
12- Method D 3972-90	ASTM 1994	Radiochemical separation, electrodeposition on stainless steel disk; count by alpha spectrometer.	na	na	na	This method applies to soluble uranium as well as to any uranium that might be present in suspended matter in the water sample.
13- Method R-1182-76	GSI 1977	Radiochemical separation, electrodeposition on stainless steel disk; count by alpha spectrometer.	na	na	na	This method is applicable to most fresh water and saline waters.
14- Method U-02	DOE 1990	Radiochemical separation, micro precipitation; count by alpha spectrometer.	na	na	na	This procedure has been used to analyze soft tissue, vegetation, water, and air filter samples.
15- Method D 5174-91	ASTM 1994	An aliquot of the sample pipetted directly (for screening purposes) or after chemical treatment into the phosphorimeter cell; count by laser phosphorimeter.	0.05 ppb	na	na	This method covers the determination of total uranium in water.

[a] Minimum detectable level is defined as the minimum detectable concentration reported for the method at the 99% confidence level (EPA 1980) or at the 95% confidence level (EPA 1976).

[b] na - information not available.

29 Unregulated Drinking Water Sources Exceeding Drinking Water Standards[8]

Water Source	Navajo Nation Chapter	Uranium (µg/L) MCL 30 µg/L	Gross Alpha (pCi/L) No MCL	Radium 226+228 (p/Ci) MCL 5 p/Ci	Arsenic (µg/L) MCL 10 µg/L	Lead (µg/L) 15 µg/L action level	Selenium (µg/L) MCL 50 µg/L
Badger Springs	Cameron	39			31		
3A-155 Tohatchi Spring	Cameron	120			40		
3A-PHS-32 Paddock Well	Cameron	55			25		
16-4-10 Lime Ridge	Church Rock	260	108	9.6			
16K-336	Church Rock			5.78	11		
Becenti Trail Spring	Church Rock	110					
17M-99	Cornfields	100					
12-7-12 Ellison Well	Cove	61					
8A-180	Dennehotso	31					
8A-179	Dennehotso	46					
17M-66	Ganado	31			18		
17T-559	Greasewood	78					
17-8 Snake Well	Greasewood	32			20		
16B-38 Paddy Martinez	Haystack	54					
16T-521 Platero	Haystack	63	20.6		55		
17H-146	Indian Wells	69			51		
Pigeon Springs	Iyanbito	88.5					
5M-74 Box Springs	Leupp	35					
10T-241A	Many Farms	44					
Monument Pass	Oljato	39	16.37		11		
8K-433	Oljato	130		9.57	11		
17T-519	Steamboat			8.19			
17T-545	Steamboat	32.85			26.8		

8 January 2013 Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation—five Year Plan Summary Report.

Water Source	Chapter	Uranium (µg/L) MCL 30 µg/L	Gross Alpha (pCi/L) No MCL	Radium 226+228 (p/Ci) MCL 5 p/Ci	Arsenic (µg/L) MCL 10 µg/L	Lead (µg/L) 15 µg/L action level	Selenium (µg/L) MCL 50 µg/L
9Y-12	Red Mesa / Mexican Water	700				68	140
9Y-32	Red Mesa	51			21		
16T-519 Largo Corral	Smith Lake	34			32		
9T-550	Sweetwater	31	18.93	6.21			
9T-586	Sweetwater		22.43				
10R-51B	Tselani / Cottonwood	31					

Note that the water sources cited were not sampled from Public Water Supply Systems. The MCLs were used for comparison purposes only. The results are not definitive with respect to attribution from mining versus naturally occurring sources.

APPENDIX B

Articles by Professor Clifford Anderson

Ref: *Erosion of Soils and Scour of Foundations*, Proceedings of the Geo-Frontiers 2005 Congress, Austin, Texas, January 24-26, 2005, Sponsored by the Geo-Institute of ASCE, Edited by Jean-Louis Briaud, and Shobha K. Bhatia, Geotechnical Special Publication No. 135, Published by the American Society of Civil Engineers, Reston, VA; 2005; ISBN 978-0-7844-0781-3

Gravel Admixtures for Erosion Protection in Semi-Arid Climates

Clifford E. Anderson[1], PE, PhD and John C. Stormont[2], PE, PhD

[1]University of New Mexico, Department of Civil Engineering, Tapy Hall, MSC01-1070, Albuquerque, New Mexico 87131, Phone: (505)277-4556, Fax: (505)277-1988, email: cliff@ahymo.com

[2]University of New Mexico, Department of Civil Engineering, Tapy Hall, MSC01-1070, Albuquerque, New Mexico 87131, Phone: (505)277-6063, Fax: (505)277-1988, email: jcstorm@unm.edu

Abstract

Erosion of surface soils is a particular concern in climates with high intensity storms and low native plant density such as the semi-arid Southwestern US. In this case, erosion may occur by the formation of rills and gullies that can result in significant maintenance expense and/or the loss of function of the soil layer. For example, significant erosion from a surface cover system designed to isolate buried wastes will compromise their barrier function. Estimates of erosion from single precipitation events in semi-arid climates suggest that erosion from a single 100-year event can be more than five times the average annual erosion. Thus, there is a need to design for specific storm events rather than using annual averages.

An effective erosion barrier for conditions associated with semi-arid climates can be designed by combining gravel with native soils into a gravel admixture layer. As finer portions of the soil are removed by erosive forces, the larger particles remain behind and form an "armored" layer that inhibits the formation of deep rills and gullies. The area of armored layer formation is restricted to zones where erosive flows are concentrated. This process is observed in nature in the formation of armored layers in sand and gravel bed arroyos. In dry climates, a gravel admixture layer can have advantages over other treatments such as rip-rap, gravel veneers, vegetation and geosynthetics. For example, in contrast to some other treatments, an admixture will have little impact on vegetation or the soil-water balance.

A procedure for design of gravel admixtures is given. Input to the design includes physical properties of the surface layer (slope, length) and the intensity of the

application of the water (precipitation rates, infiltration – runoff relationship, and off-site flows). The design results include the size of the gravel, percentage of gravel and depth of the admixture layer. In addition, modification of the hydraulic properties of the native soils from the added gravel can be estimated.

The successful application of a gravel admixture layer into a cover system for a Superfund site is described. The gravel admixture layer was designed to provide protection from a 100-year precipitation event and included the following specifications: 50% gravel (1:1 by weight with soil), size gravel at 1.6 to 3.2 cm; and a 16 cm layer thickness. After seven years, the cover shows no signs of significant rill formation or other degradation.

Introduction

Regulations for closure of municipal waste landfills typically follow the Federal regulations established by the Resource Conservation and Recovery Act (RCRA, 1976, Subtitle D program, 40 CFR 258). These regulations require the top soil layer to have a slope not less than 0.03 m/m, and not greater than 0.05 m/m. This minimum slope is required because the surfaces of a landfill are subject to substantial local settlement due to the normal process of decomposition of solid waste. Covers for hazardous waste remediation will generally have similar slopes. The application of minimum slope criteria provides for a surface that is relatively free of local depressions and pond areas where excess precipitation can accumulate. To minimize the future occurrence of ponding and to limit infiltration, it is common for designers and regulators to consider slopes approaching the 0.05 m/m limit. Steeper slopes of 0.08 or 0.10 m/m have been considered for some sites.

In some climate zones, a vegetative cover will form a protective blanket that effectively prevents erosion on a cover system. But for arid and semi-arid areas in the southwest United States, minimal rainfall and warm climate creates sparse vegetation. In many areas the natural vegetation will cover only 10 to 20 percent of the surface. The native plants commonly establish root systems that collect moisture from wide areas and store moisture during drought periods. It is possible to provide revegetation with nonnative species to provide a higher plant density, but such attempts are frequently not sustainable. In order to maintain the nonnative species supplemental watering may be required, but introduction of water is not normally advisable for long-term post-closure of landfills.

If native plants are used for southwestern landfill cover systems, a continuous erosion blanket is not likely to be created. Much of the land surface will be exposed to the impacts of rainfall and surface runoff, with the resulting transport of soil through erosion. Surface erosion is a function of the intensity of rainfall and the steepness of the terrain. The impact from raindrops initiates local soil movement, but it is the conveyance across slopes that causes local soil movement to become erosion. The creation of greater cover slopes can have consequences for erosion that will become obvious only after severe rainfall events.

Erosion will not usually occur as a uniform lowering of the surface, but by the formation of rills or small gullies. Rills are the smallest channels formed by runoff, and gullies are the somewhat deeper channels. The distinction between the two is not precise, but both are formed where no defined channel originally existed. Rills and gullies have the potential to cut through the top soil (erosion) layer of a cover system and damage the underlying barrier soil layer or liner. Such damage would compromise the cover system protection.

To assess the impact of potential surface slopes, a typical cover environment in southeastern New Mexico was investigated. Here, erosion was estimated using both an empirical equation and mathematical modeling of the physical processes. These procedures were applied to a New Mexico location.

Estimating Erosion with the Revised Universal Soil Loss Equation

An empirical procedure applicable to landfill erosion evaluation is the Revised Universal Soil Loss Equation (RUSLE). This equation is described in detail in *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)* (Renard, et al., 1997). The RUSLE was derived from the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The RUSLE has been used throughout the United States and is particularly directed to the prediction of erosion from agricultural lands, but the procedures do include methodology for use in pasture, range and idle land, and for areas disturbed by construction. The RUSLE equation is:

$$A = R\ K\ L\ S\ C\ P$$

where A is the computed soil loss per unit area, R is a rainfall runoff erosivity factor, K is a soil erodibility factor, L is a slope length factor (a ratio of field length to a 22.1 m test plot), S is a slope steepness factor (a ratio of field slope to a 0.09 meter per meter slope), C is cover management factor, and P is a support (conservation) practice factor. The RUSLE is limited to the determination of average annual erosion rates and cannot establish erosion from specific events and peak erosional years. Additionally, there is no method within the RUSLE procedure to determine the depth or magnitude of gully or rill erosion that may be an integral part of the erosion process.

Erosion Modeling with AHYMO and WEPP

There is no known procedure that presents an accurate measure of the physical processes concerning erosion on a cover. However, there are several procedures that combine modeling of some physical processes along with application of empirical equations. One applicable methodology includes the determination of storm water runoff hydrographs using hydrologic modeling, the estimation of sediment wash loads (fine silts and clays that can be suspended in runoff) using the storm-based Modified Universal Soil Loss Equation (Williams, 1975), and estimation of channelized sediment transport rates using regression equations developed from more complex sediment transport procedures. This computational methodology has been included in the *AHYMO Computer Program* (Anderson, 1997). The sediment volume for any storm event can be computed from the above procedure. All of the runoff events for a period can be accumulated to obtain an average annual volume. An average annual sediment yield can also be computed by using a statistically weighted function of the 2, 5, 10, 25, 50 and 100-year sediment yields.

The Water Erosion Prediction Project (WEPP) model is a process-based model that considers rill and interrill erosion (Flanagan and Nearing, 1995). For a slope without a pre-existing channel, runoff rates and durations are used to calculate delivery of interrill sediment quantities, and rill erosion and deposition are estimated assuming rectangular rill geometry and a rill density statistic. Databases containing soil properties, climate parameters, and land treatments are available within the program. Surface and subsurface hydrology, winter processes, irrigation, plant growth and residual decomposition are included in the program. The program is capable of developing sediment yield estimates from single storm events (such as the 10-year event) or continuous climate conditions to produce annual values.

Site specific conditions are required to utilize modeling with the AHYMO and WEPP programs. A typical site in southeastern New Mexico was selected in order to provide a comparison of predicted erosion using the empirical RUSLE procedure and modeling methods.

Input Parameters for Erosion Simulations

In order to simulate runoff from a typical landfill using numerical methods, it was necessary to establish some physical parameters that would be used in the models. For this erosion potential analysis the following values were selected: cover system area at 2.02 ha (5.0 acres), surface dimensions at 142.2 m by 142.2 m, a coarse sandy loam or loamy fine sand surface soil, median bed material gradation (D_{50}) of 0.50 mm, and a ground cover with 10-percent native grass cover. Surface slopes of 0.02, 0.05 and 0.08 m/m were used to simulate three potential surface configurations.

Rainfall is the driving condition for most moisture and erosion that can impact a cover system. While snow melt may also produce moisture, it is of lesser consequence for erosion throughout much of the southwest US. The 24-hour precipitation amounts for a site in New Mexico were obtained from the *Precipitation Frequency Atlas of the Western United States, Volume IV-New Mexico (NOAA Atlas)* (National Weather Service, 1973) as shown in Table 1.

Table 1. Precipitation for 24-hour storm	
Return period	From NOAA Atlas maps
2-year 10-year 100-year	4.95 cm 8.13 cm 12.70 cm

For erosion event computation, extreme rainfall events must be accurately represented. Therefore, revised synthetic precipitation data was created using the Extreme Value Type I distribution and procedures described in *Applied Hydrology* (Chow, et al, 1988). This resulted in 137 daily events greater than 2.2 cm for a 100-year simulation, and extreme event values in agreement with the NOAA Atlas.

The simulation of runoff and erosion required that the depth of cumulative precipitation be simulated throughout a 24-hour period, with special concern about the rainfall intensity during the peak hour. Table 2 shows the distribution of a typical rainfall event based on the 24-hour and 1-hour values from the NOAA Atlas. The data from Table 2 was applied to each of the 137 daily rainfall quantities to form 137 rainfall distribution tables.

Table 2. Rainfall distribution factors							
Time	24-hr	6-hr	1-hr	30-min	15-min	10-min	5-min
Percent of 24-hour	100.0	80.0	60.0	47.4	34.2	27.0	17.4
Percent of 1-hour	166.67	125.0	100.0	79.0	57.0	45.0	29.0

Results from the Revised Universal Soil Loss Equation Analysis

The average annual sediment yield from the RUSLE is tabulated in Table 3. These values are based on a rainfall-runoff factor (R) of 80; a length-slope factor (LS – with a high ratio of rill to interrill erosion) of 0.51 at a 0.02 m/m slope, 1.69 at a 0.05 m/m slope, and 2.97 at an 0.08 m/m slope; a soil erodibility factor (K) for coarse sandy loam or loamy fine sand of 0.20; a cover factor for 10-percent native grass of 0.30; and a conservation practice factor of 1.0. Table 3 summarizes the results from the RUSLE for the 2.02 ha (5.0 acre) site.

Table 3. Average annual sediment yields based on the RUSLE (kg)		
Slope = 0.02 m/m	Slope = 0.05 m/m	Slope = 0.08 m/m
11100	35700	64600

Results from the AHYMO and WEPP Modeling

When the 137 largest rainfall events of the 100-year period were evaluated with the AHYMO computer program, only 115 events showed measurable runoff. A summary of the AHYMO sediment yields is contained in Table 4. The average annual sediment yields computed by the AHYMO program are within about 15 percent of the values computed with RUSLE.

Table 4. Sediment yield using AHYMO

Event frequency	24-hr rain (cm)	Sediment (kg) at 0.02 m/m slope	Sediment (kg) at 0.05 m/m slope	Sediment (kg) at 0.08 m/m slope
100-year	12.70	54800	184300	326500
10-year	8.13	23400	79400	141600
2-year	4.95	6200	21500	38800
Average annual	-----	9300	31800	57000

The WEPP program was also used to compute storm water runoff and sediment yields for the 2, 10 and 100-year events as well as the annual average for 100 years of simulated climate. Table 5 presents sediment yields computed with the WEPP model for the 0.02, 0.05 and 0.08 m/m slopes. The sediment yields computed by the WEPP program are substantially lower than the values computed with the RUSLE and the AHYMO program. These results highlight the variability of erosion estimates made with different methods, and suggest caution when utilizing estimated erosion quantities.

Table 5. Sediment yield using WEPP

Event frequency	24-hr rain (cm)	Sediment (kg) at 0.02 m/m slope	Sediment (kg) at 0.05 m/m slope	Sediment (kg) at 0.08 m/m slope
100-year	12.70	16800	50500	85100
10-year	8.13	8600	28700	49300
2-year	4.95	1900	12900	22900
Average annual	-----	1800	8600	15400

The sediment values from RUSLE and AHYMO all exceed the conventional regulatory limit of annual permissible sediment loss of 4500 kg/ha (2 tons/acre), whereas the WEPP results suggest that only the steepest slope exceeds this annual limit. Another observation from these results is that results from single storm events from both WEPP and AHYMO can be many times the annual amount.

If the sediment yield computed for a 100-year event were uniformly distributed over the entire 2.02 ha area the effect on a typical cover would be minimal, with a loss of 0.05 to 0.17 cm for a 0.02 m/m slope, 0.16 to 0.57 cm for a 0.05 m/m slope, and

0.25 to 1.0 cm for a 0.08 m/m slope. However, rill or gully erosion is likely to be concentrated over 2 to 5 percent of the cover area, resulting in average rill or gully depths 20 to 50 times the values computed for uniform erosion. For all surface slopes, gullying could adversely affect cover performance.

Design of Erosion Protection

In dry climates, a surface gravel veneer or gravel admixture layer (Waugh and Petersen, 1994) can be utilized to provide erosion protection. A gravel veneer is constructed by placing a 2 to 5 cm thick layer on the soil surface. The gravel must be of sufficient size that it will not be substantially displaced during a major storm event. Rounded gravel with a diameter of 1.3 to 5 cm (½ to 2 in.) is typically used. A gravel layer will reduce surface erosion due to runoff and wind erosion, hold seed in place until it can germinate, and moderate the temperature of the underlying soil. In addition, moisture may increase in the upper most layer of soil allowing vegetation to become established. Experimental studies have shown that a gravel mulch can significantly reduce sediment yield from a cover (Finley et al., 1985; Wischmeier and Smith, 1978).

A gravel veneer can reduce the evaporation rate and may create a habitat for deep-rooted plants (Waugh and Petersen, 1994; Kemper et al., 1994). This reduced evaporation may discourage the use of a surface gravel veneer. For some climate conditions, the increased moisture may increase plant evapotranspiration and offset the loss in direct evaporation. There is no published information revealing whether the added evapotranspiration will offset the reduced evaporation. The use of a gravel veneer may need to be a site specific decision.

An alternative to a surface gravel layer is a gravel admixture. A gravel admixture can be used in combination with vegetative treatments. Waugh and Petersen (1994) suggest that moderate amounts of gravel mixed into the cover topsoil will control both water and wind erosion with little effect on vegetation or soil-water balance. Brakensiek and Rawls (1994) have evaluated the effects of rock and soil mixtures on permeability and unsaturated soil properties. The design of a gravel admixture layer should be based on the need to protect the soil cover from water and wind erosion. A gravel admixture generally protects a cover from long-term wind erosion; the protection from water erosion will depend on the depth, velocity, and duration of water flowing across the landfill cover. These flow values can be established from the physical properties of the cover (slope, convex or concave grading, slope uniformity, and length of flow paths) and the intensity of the application of water (precipitation rates, infiltration - runoff relationship, and off-site flows). For the arid and semi-arid Southwest, runoff from severe storm events usually presents the critical stress on gravel admixture stability.

Based on the above concerns, the gravel admixture for a landfill cover should be based on maintaining long term ecological stability and protection of the soil cover from runoff generated by a major storm event. The design condition for the major storm event will be to prevent rill or gully erosion from penetrating into the soil layer. The following steps can be used to design a gravel admixture:

a) Establish physical parameters for the cover including area, maximum slope and slope length. Estimate the width of the surface that contributes to individual gully formation. A width of approximately 25% of the slope length is appropriate for many uniformly graded surfaces at slopes less than 10%. The slope length and width establishes the area contributing to formation of a rill or rill zone.

b) Determine rainfall quantities for the design storm from historic information, such as the NOAA Atlas 2. Determine 5, 10, 15, 30 and 60-minute rainfall intensities. Select an appropriate design storm; commonly a 10-year to 100-year event is used.

c) Using appropriate surface infiltration conditions, establish a runoff hydrograph for the design storm event. Runoff based on the rational method, the initial abstraction-uniform infiltration method or the Green-Ampt method is commonly used.

d) Compute sheet flow erosion using the MUSLE (Williams, 1975) with a wash load factor based on local climate conditions.

e) Compute rill or channelized erosion quantity from the runoff hydrograph based on the Meyer-Peter, Muller-Woo (MPM-Woo) Method (Mussetter, et al., 1994) or other total sediment load equation, calibrated for local conditions.

f) Compute the rill geometry using the flow rate and soil grain relation by Simons, Li and Associates (1982, equation 5.7):

$$b = 37\,(Q_m^{0.38} / M^{0.39})$$

where b is the width of flow in feet, Q_m is the dominant discharge in cfs and M is the percentage of silt and clay. For arid alluvial conditions use Q_m at 10 to 20% of the peak flow, Q. For shallow sections:

$$b = 0.5\,(b / d_h)^{0.6}\,F_r^{-0.4}\,Q^{0.4}$$

where d_h is the hydraulic depth in feet, F_r is the Froude number (assumed to be approximately 1.0 for moderately steep natural channels) and Q is the peak flow in cfs. From these equations the following equations can be derived to estimate the rill properties:

$$d_h = (1 / 12.03)\,M^{0.2597}\,Q_m^{0.4136}$$

$$b = 363.6\,M^{-0.6286}\,d_h^{0.9188}$$

When F_r is computed to be much less than 1.0, the equations should be modified to use the computed F_r value. Use locally calibrated geomorphologic factors to estimate channelized flow spacing and channel width-to-depth ratios.

g) From the hydraulic analysis of the cover surface, compute the critical particle size, D_c, using the Shield's relation (Graf, 1971):

$$D_c = \tau / (F^* (\gamma_s - \gamma))$$

Where τ is the bed shear stress in psf, F^* is Shield's dimensionless shear stress (0.047 is commonly used), and γ_s and γ are the unit weights in pcf of the particle and the water. The bed shear stress, τ, is given by:

$$\tau = \gamma \, d_h \, S$$

where S is the bed slope in m/m. The D_c is the minimum size required to maintain an armored or stable channel configuration for the design flow event.

h) Based on the percentage of gravel in the gravel admixture layer, compute the depth of scour, Y_s, necessary to establish an armor layer with the equation:

$$Y_s = Y_a \, (1 / P_c - 1)$$

where Y_a is the armor layer thickness and P_c is the decimal fraction of material greater than the incipient particle size. The value of Y_a should be 3 to 4 times the D_c, with a value of 4 times D_c commonly used for small diameters (D_c < 75 mm).

i) Compute the total thickness of the gravel/soil admixture layer, Y_{total}, as:

$$Y_{total} \geq Y_s + Y_a$$

The thickness of the gravel/soil admixture layer will also depend on the maximum diameter of the gravel, D_{max}, in the admixture layer so that:

$$Y_{total} \geq Y_s + (2 \, D_{max})$$

The value of D_{max} should generally be less than 6 to 8 times D_c.

Additionally, the total recommended depth for the gravel admixture may incorporate design safety factors based in uncertainty in material properties, runoff quantities and geomorphologic factors. This gravel admixture design procedure is not appropriate for channels or locations where surface flows are intentionally concentrated. Further, application of the procedure may not be appropriate for slopes in excess of 0.1 m/m.

Application of Design Parameters

A gravel admixture layer was applied in 1997 to a 0.31 ha (0.76 ac) demonstration landfill cover at a Superfund site near Farmington, New Mexico. The surface slope in this cover was at 0.05 m/m. The gravel admixture was designed to provide protection from a 100-year precipitation event and included the following specifications: proportion of gravel to total at 50 percent (1 part gravel to 1 part soil); size at 1.6 to 3.2 cm (0.65 to 1.3 in.); and thickness of layer at 16 cm (6 in.). After seven years, the cover shows no signs of significant rill formation. During this period 11 rainfall events greater than 1 inch in 24-hours occurred. No events near the 100-year magnitude have been measured.

A summary of the design parameters are given below:

Design storm for erosion stability = 100-year frequency (1% per year)
Top slope = 0.05 m/m (5%)
Percentage of gravel = 50% of total (1 part gravel to 1 part soil)
Cover soils = silty clayey sand with D_{50} = 0.20 mm.
Overland flow slope length = 61 m (200 ft.)
Peak flow = 0.23 m^3/s per ha (3.32 cfs per acre)
Maximum channel velocity = 0.64 m/s (2.11 ft/s)
Hydraulic depth of channel flow = 25.6 mm (0.084 ft.)
Bed shear stress = 1.28 kg/m^2 (0.262 psf)
Critical particle diameter = 16.5 mm (0.054 ft.), use 19 mm (0.75 in.)
Required thickness of armor layer = 8 cm (3.0 in.)
Scour depth = 8 cm (3 in.)
Thickness of gravel/soil admixture layer = 16 cm (6 in.)
Gravel gradation = 1.9 to 3.8 cm (¾ to 1½ in.)

Conclusions

The function of a landfill can be improved by construction measures designed to control erosion. The slope of a final cover can have a profound impact on the amount of erosion and on the size of rills or gullies. In arid and semi-arid climates, a significant percentage of erosion and formation of rills may come from single events that are represented by 10-year to 100-year storms. A single 10-year storm can to produce erosion quantities more than two times the average annual erosion and a 100-year storm can produce five times the average annual erosion. While mitigative measures such as revegetation and application of organic mulches may reduce erosion, mechanical stabilization by a gravel veneer or a gravel admixture layer will likely be required to prevent water erosion in the arid and semi-arid Southwest. The design method for gravel admixtures presented here may serve as an outline for further erosion investigations and provide guidance for future designs of gravel-soil admixture layers.

References

Anderson, C.E. (1997) *AHYMO (AHYMO_97) Computer Program User's Manual (An Arid Lands Hydrologic Model)*, Anderson-Hydro, Albuquerque, New Mexico.

Brakensiek, D.L. and W.J. Rawls (1994) Soil containing rock fragments: effects on infiltration. In *Catena*, 23, 99-110.

Chow, V.T., D.R. Maidment and L.W. Mays. (1988) *Applied Hydrology.* Mc-Graw-Hill, New York, N.Y.

Finley, J.B., M.D. Harvey and C.C. Watson (1985) Experimental study: erosion of overburden cap material protected by rock mulch. In *Seventh Symposium on Management of Uranium Mill Tailings, Low-Level Waste and Hazardous Waste*, February 6-8, 1985. Colorado State University, Fort Collins, Colorado, 273-282.

Flanagan, D. C. and M. A. Nearing (1995) *USDA – Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation*, NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana

Graf, W.H. (1971) *Hydraulics of Sediment Transport*. Mc-Graw Hill, New York, NY.

Kemper, W.D., A.D. Nicks and A.T. Corey (1994) Accumulation of water in soils under gravel and sand mulches. In *Soil Science Society of America Journal*, 58, 56-63.

Mussetter, R.A., P.F. Lagasse and M.D. Harvey (1994) C.E. Anderson contributing editor. *Sediment and Erosion Design Guide*. Albuquerque Metropolitan Arroyo Flood Control Authority, Albuquerque, New Mexico.

National Weather Service. (1973) *NOAA Atlas 2, Precipitation-Frequency Atlas of the Western United States, Volume IV-New Mexico.* U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McKool and D. C. Yoder. (1997) *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE*). U.S. Department of Agriculture, Agriculture Handbook No. 703, 404 pp.

Simons, Li and Associates. (1982) *Engineering Analysis of Fluvial Systems*. Fort Collins, CO.

Waugh, W.J. and K. L. Petersen (1994) Paleoclimatic data application: long-term performance of uranium mill tailings repositories. In *Climate Change in the Four Corners and Adjacent Regions: Implications for Environmental Restoration and Land Use Planning, Proceedings of the Workshop*. September 12-14, 1994. Mesa State College, Grand Junction, Colorado. US Dept. of Energy, CONF-9409325, 163-185.

Williams, J.R. (1975) Sediment-yield prediction with universal equation using runoff energy factor. In *Present and Prospective Technology for Predicting Sediment Yields and Sources, Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, November 28-30,1972.* ARS-S-40, U.S. Department of Agriculture, Agricultural Research Service.

Wischmeier, W.H. and D.D. Smith. (1978) *Predicting Rainfall Erosion Losses - a Guide to Conservation Planning.* Agriculture Handbook Number 537, U.S. Department of Agriculture, Science and Education Administration, Washington, DC.

Reference: Pages 1054 to 1063; *Geotechnical Special Publication No. 210, Scour and Erosion, Proceedings of the Fifth International Conference on Scour and Erosion (ISE-5)*; November 7-10, 2010; San Francisco, CA, USA; S.E. Burns, S.K. Bhatia, C.M.C. Avila and B.E. Hunt editors; published by the American Society of Civil Engineers, Reston, VA; 2011; ISBN 978-0-7844-1147-6.

Design of Erosion Protection at Landfill Areas with Slopes Less than 10%

Clifford Anderson[1], M. ASCE, PE, PhD, D.WRE and Steve Wall[2]

[1]Department of Engineering, Central Connecticut State University, 1615 Stanley Street, New Britain, CT 06050-4010, USA, email: cliff@ahymo.com

[2]Office of Pollution Prevention and Solid Waste (WST-7), US EPA Region 9, 75 Hawthorne St., San Francisco, CA 94105, USA, email: Wall.Steve@epamail.epa.gov

ABSTRACT

Surface water can enter landfill waste zones from top surface areas and erosion of the top surface can cause wash-out of waste material. Landfill covers at these locations must prevent surface water infiltration and provide erosion resistance. In arid climates a rock veneer can be used to reduce erosion, but this will increase infiltration and reduce surface evaporation making it more likely that surface water will enter waste zones. An alternative is the placement of a mix of soil and gravel as a surface layer; the mix is commonly called a gravel admixture. Studies of gravel admixture layers have shown they provide greatly reduced surface infiltration rates over gravel alone, and have evaporation rates very similar to soil alone. A method is presented to compute the rock and soil gradations, and thicknesses of gravel admixture layers based on peak flow, slope and the formation of surface channelization. The procedure is used to select gradation ranges and applicable slope lengths for a landfill cover.

INTRODUCTION

Regulations for closure of municipal waste landfills typically follow the Federal regulations established by the Resource Conservation and Recovery Act (RCRA, 1976, Subtitle D program, 40 CFR 258). These regulations require the top soil layer to have a slope not less than 0.03 m/m, and not greater than 0.05 m/m. This minimum slope is required to prevent surface ponding because a landfill is subject to substantial local settlement due to solid waste decomposition. To minimize ponding and infiltration, designers commonly consider slopes approaching the 0.05 m/m limit. Steeper slopes of 0.08 or 0.10 m/m have been considered for some sites.

In some climate zones a vegetative cover can be used to provide an effective erosion blanket at a landfill cover system. However, in many of the arid and semi-arid areas of the southwest United States, the natural vegetation will cover only 10 to 20 percent of the surface (Anderson and Stormont, 2005). If native plants are used for southwestern landfill cover systems, a continuous erosion blanket is not likely to be created. The impact from raindrops initiates local soil movement, but it is the conveyances across slopes that cause local soil movement to become erosion. The creation of longer or steeper cover slopes can have consequences for erosion that will become obvious only after severe rainfall events.

In dry climates, a gravel surface mulch or veneer can be designed to provide erosion protection. A gravel veneer is typically constructed by placing a 3 to 10 cm thick layer on the soil surface. The gravel must be of sufficient size that it will not be substantially displaced during a major storm event. Rounded gravel with a diameter of 1.3 to 5 cm (½ to 2 in.) is typically used. Experimental studies have shown that gravel mulch can significantly reduce sediment yield from a cover (Finley et al., 1985; Wischmeier and Smith, 1978). However, there are two properties of a gravel veneer that discourage landfill use: 1) it can reduce the evaporation rate, and 2) it may create a habitat for deep-rooted plants (Waugh and Petersen, 1994; Kemper et al., 1994).

Some landfills in arid climates are being constructed with thicker soil layers in place of clay or geomenbrane layers because they can provide equivalent or superior performance at a lower cost. The successful function of soil-only landfill covers is very dependent upon the ability of the surface layer to reduce surface infiltration and allow evaporation to remove moisture from the soil cover layers. Waugh and Petersen (1994) suggest that moderate amounts of gravel mixed into the cover topsoil will control both water and wind erosion without the negative effect on vegetation and soil-water balance caused by a gravel veneer. When a mix of soil and gravel is used as a surface layer, the mix is commonly called a gravel admixture. If the gravel admixture contains a sufficient quantity of appropriately sized rock, a gravel admixture will also provide erosion protection in a manner similar to placement of rock alone. The procedures described in this document can be used to guide the design of a gravel admixture that will provide for reduced surface erosion, and create a surface with water infiltration and evaporation similar to a natural soil.

The analyses presented in this document generally apply to landfill top surface areas with slopes between 3% and 10%. Flatter sloped areas may have settlement and ponding conditions that may not be adequately addressed by ordinary soil covers. The computed admixture layer thicknesses may become large for slopes steeper than 10% when slope lengths and runoff quantities also become large. While there is nothing in the procedure that specifically limits the use of gravel admixtures to slopes less than 10%, construction economics may lead to other surface treatment methods.

The design of a gravel admixture layer to protect a landfill surface requires evaluation of small watershed hydrology and hydraulics, and the design of the conveyances where water is expected to flow. In the case of most uniformly graded landfill surfaces, a fixed flow path or channel may not be constructed into the surface. The site physical conditions and measurements completed after events at similar areas can be used to predict surface flow conditions. For a landfill top surface in the arid and semi-arid areas of the southwest United States a 100-year event is a suggested design condition, but other site conditions may warrant use of different frequencies.

PEAK FLOW AND UNIT DISCHARGE

For any given watershed, the 100-year frequency event peak flow (Q_{100}) can be determined from a basic hydrologic analysis, such as with the Rational Method or NRCS Curve Number (*CN*) procedure. Peak flow during the storm event is the most important hydrologic property to accurately predict. For a planar watershed surface with an identified length, but a width that can be identified only after erosion has occurred, the recommended watershed width for runoff computations should be 25% of the watershed length. The dominant discharge peak flow (Q_m) can be evaluated by considering the statistically weighted average of the peak runoff occurring over a long period, for example 100 years. In the arid southwestern the Q_m can be estimated at 10% of Q_{100}. For a wide channel section where:

$$\frac{A}{WP} = \frac{b\ d_h}{b + (2\ d_h)} = d_h \qquad \text{at} \qquad b \gg d_h \tag{1}$$

Manning's equation for open channel flow can be written to solve for the width of flow (b) as:

$$b = Q_{100}\, n\ s^{-0.5}\ d_h^{-1.667} \tag{2}$$

where:	b	is the width of flow (m),
	A	is the area of flow (m^2),
	WP	is the wetted perimeter (m),
	d_h	is the hydraulic depth (m),
	Q_{100}	is the peak flow at 100-year frequency (m^3/s),
	n	is the Manning's roughness coefficient,
and	s	is the slope of the channel profile (m/m).

A geomorphologic equation to describe the width of open channel flow as a function of dominant discharge and percentage of silt and clay is given in *Engineering Analysis of Fluvial Systems* (Simons, Li and Associates, 1982, p 5.47) and in *Watershed and Stream Mechanics* (D. B. Simons, R. M. Li, et al., 1980, p. 4-37). While this equation was not specifically adapted to address landfill cover runoff, it has been found to provide appropriate values for this application. The geomorphologic equation (converted from US customary to metric form) is:

$$b = 43.7\ Q_m^{0.38}\ M^{-0.34} \tag{3}$$

where:	Q_m	is the dominant discharge (m^3/s),
and	M	is the percentage of silt and clay in the channel perimeter.

The value of Q_m can be computed as:

$$Q_m = Q_{100}/DD_{factor} \tag{4}$$

where: DD_{factor} is the dominant discharge factor = Q_{100}/Q_m (Use a value of 10),
and Q_{100} is the peak flow at 100-year frequency (m^3/s).

Manning's equation, [2], and the geomorphologic equation, [3], are both expressed as functions of b, so they can be equated to become:

$$Q_{100}\, n\ s^{-0.5}\ d_h^{-1.667} = 43.7\ Q_m^{0.38}\ M^{-0.34} \tag{5}$$

Equation [4] and equation [5] can be combined to obtain:

$$d_h^{-1.667} = 43.7 \; (Q_m/Q_{100}) \; Q_m^{-0.62} \; n^{-1} \; s^{0.5} \; M^{-0.39} \qquad [6]$$

Then equation [6] can be reformulated to obtain the hydraulic depth:

$$d_h = \; (43.7)^{-0.6} \; (Q_m/Q_{100})^{-0.6} \; Q_m^{0.372} \; n^{0.6} \; s^{-0.3} \; M^{0.234} \qquad [7]$$

The channel profile slope, *s*, and the percentage of silt and clay, *M*, are physical properties that can be measured at a watershed. The Strickler relation (Anderson, et al, 1970) can be used to estimate the Manning's roughness coefficient, *n*, with the following equation:

$$n = 0.0488 \; (D_{50}/1000)^{0.167} \qquad [8]$$

where: D_{50} is the median size of the rock riprap (mm).

The value of D_{50} can be estimated from a preliminary analysis, and this value can then be used to compute an interim D_{50} for the erosion protection. The final value of D_{50} can be obtained with an iterative process. Including equation [8] in equation [7] results in:

$$d_h = (43.7)^{-0.6} \left(\frac{Q_m}{Q_{100}}\right)^{-0.6} \; Q_m^{0.372} \left[0.0488 \left(\frac{D_{50}}{1000}\right)^{0.167}\right]^{0.6} s^{-0.3} \; M^{0.234} \qquad [9]$$

Equations [3] and [9] describe the flow width and depth based on the geomorphologic equation of Simons, Li and Associates. Except for the D_{50}, all of the values in these equations can be estimated from physical watershed properties. The equations can also be used to compute the 100-year event unit discharge, Q_{100}/b, and the width-to-depth ratio, b/d_h. While the dominant discharge, Q_m, is used in equation [9], the computed hydraulic depth, d_h, represents the depth from a 100-year frequency event.

A second geomorphologic parameter is the width-to-depth ratio of the flowing water. For arid and semi-arid locations the maximum width-to-depth ratio is approximately 40, although other values may need to be considered for local conditions. If the width-to-depth ratio, b/d_h, using equations [3] and [9] exceeds 40, the b and the d_h should to be re-computed to maintain a width-to-depth ratio of 40. The width-to-depth relation can be represented with the following equation:

$$b = F \;\; d_h \qquad [10]$$

where: F is the width-to-depth ratio. (Commonly a value of 40)

Equation [2] and equation [10] can be combined to obtain:

$$Q_{100}\, n\; s^{-0.5}\;\; d_h^{-1.667} = F\;\; d_h \qquad [11]$$

This equation can be reformulated to compute the hydraulic depth as:

$$d_h = \; [(Q_{100}\, n)/F]^{0.375}\, s^{-0.1875} \qquad [12]$$

Equations [10] and [12] describe the flow width and depth based on a defined width-to-depth ratio. Equations [10] and [12] should be used whenever the b/d_h computed from equations [3] and [9] exceeds 40. Using equations [3] and [9], or equations [10] and [12], the flow velocity, V_{100}, the Froude number, F_r, the width of flow, b, and the unit discharge, q_f, can be computed.

ROCK SIZES AND ADMIXTURE LAYER THICKNESS

With the flow properties established, the S. R. Abt and T. L. Johnson equation (1991) can be used to solve for the median rock size of the gravel veneer. A factor of safety of 1.2 should be applied to the rock size equation as recommended on page 967 of the Abt and Johnson paper. The Abt and Johnson equation uses the unit discharge, and profile slope to compute the median rock size when failure is expected to occur. The unit discharge is computed using the smallest b obtained from equation [3] and equation [10] so that the computed unit discharge is the maximum value computed from the two equations. The equation for unit discharge is:

$$q_f = \; Q_{100}/b \qquad [13]$$

where: q_f is the unit discharge or unit flow rate (m^2/s).

The Abt and Johnson equation with the addition of the recommended factor of safety and converted to metric form is:

$$D_{50} = \; (12\; \times 502.9)\; s^{0.43}\; q_f^{0.56} \qquad [14]$$

where: D_{50} is the median rock size of the gravel veneer.

The physical testing by Abt and Johnson did not use slopes steeper than 20% (0.20 m/m). Abt and Johnson's paper suggested that the gravel layer thickness should be 1.5 to 3.0 times the D_{50}. The D_{50} computed from equation [14] can be used to determine the rock gradation for the gravel portion of the gravel admixture layer. The following procedure is recommended:

- specify a construction minimum D_{50} ($D_{50\text{-}min}$) based on the computed value from equation [14] rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{50} ($D_{50\text{-}max}$) at 140% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).

- specify a minimum D_{100} ($D_{100\text{-}min}$) at 150% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{100} ($D_{100\text{-}max}$) at 200% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch). The constructed admixture can have a larger value with an appropriate adjustment in the layer thickness.
- specify a minimum D_{15} ($D_{15\text{-}min}$) at 45% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{15} ($D_{15\text{-}max}$) at 80% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify the coefficient of uniformity ($C_u = D_{60} / D_{10}$) with an allowable range between 1.75 and 3.0.

The Abt and Johnson physical testing used rock with an average specific gravity of 2.66. In order to use this equation without adjustment, the rock in the gravel admixture should have an average specific gravity of 2.65 or larger. This is equivalent to a particle unit weight of 2650 kg/m^3 (165 lbs/ft^3). If any rock with a smaller average specific gravity is proposed for use, the size of the D_{15}, D_{50}, D_{100}, and Y_{min} would need to be adjusted based on the ratio of the buoyant weight of the rock.

The gravel admixture should have a constructed percentage of gravel of not less than 25% and not more than 50% of the total admixture. To maintain these limits it is recommended that the design percentage of gravel be established between 30 and 45%. The total thickness of the gravel admixture layer is the sum of the minimum rock layer thickness plus the scour depth. The total admixture layer thickness is computed as follows:

- specify the minimum rock layer thickness ($Y_{min\text{-}rock}$) at the 2.0 times the $D_{50\text{-}min}$, or 1.0 times the $D_{100\text{-}max}$, whichever is larger.
- compute the scour depth (Y_s) with the equation:

$$Y_s = Y_{min-rock}\,[(100/\%Gravel) - 1.25] \qquad [15]$$

- compute the total admixture layer thickness (Y_{total}) as:

$$Y_{total} = Y_s + (1.5 \times Y_{min-rock}) \qquad [16]$$

with Y_{total} rounded to the nearest 0.025 m (1.0 inch). The minumum recommended value of Y_{total} is 0.15 m (6 inches) for slopes between 0 and 10%. The minimum recommended value of Y_{total} is 0.30 m (12 inches) for slopes greater than 10%.

% OF GRAVEL, "FINER SOIL" AND "GENERAL SOIL"

In order for the gravel admixture layer to retain its properties of reduced surface infiltration and increased evaporation, constraints must be placed on the quantity of gravel in the admixture layer and on the remaining soil that is smaller than gravel. The percentage of gravel in an admixture layer is computed by comparing the computed

$D_{50\text{-}min}$ and $D_{15\text{-}min}$ with the percentages in the proposed gradation that are at these computed sizes. For example, if a specified admixture has a higher percentage of particles larger than the computed $D_{50\text{-}min}$, the percentage of gravel in the admixture gradation is larger than with an optimal gradation. The percentage of gravel in a gravel admixture is estimated by first computing the percent of the mix that passes the computed $D_{50\text{-}min}$ and the computed $D_{15\text{-}min}$ to obtain the *% Passing* D_{50} and *% Passing* D_{15} in the proposed mix. These values are then used to estimate the percentage of gravel in the mix using the following equation:

$$\%Gravel = [1.24 \times (1 - \%PassingD_{50})] + [0.36 \times (1 - \%PassingD_{15})] \quad [17]$$

The equivalent particle size for the gravel can be found by computing the gradation particle size that corresponds to the *% Gravel*. The range of *% Gravel* in the admixture should be between 5% and 50%. For the soil material in the admixture that is smaller than gravel, the gradation is further described as “finer soil” and “general soil”. Finer soil is all soil material smaller than a #4 sieve (4.75 mm). In order to maintain good infiltration resistance and evaporation rates, the percentage of finer soil in the admixture should not be less than 34%. The finer soil should also have a minimum percentage of silt or clay size particles (particles passing a #200 sieve, or smaller than 0.075 mm) with the silt and clay at 5% to 50% by weight of the finer soils. A large percentage of clay size particles (smaller than 0.005 mm) in the finer soils could cause surface cracking, and it is suggested that clay size particles should not exceed 40% by weight of the finer soils. Additional specifications to limit the content of expansive clay and dispersive clays are recommended. For the gravel admixture, the finer soils should be between 34% and 95% by weight of the admixture. The soils that are finer than the gravel and larger than the #4 sieve (4.75 mm) are considered to be general soils. General soils are not required for the gravel admixture but they are expected to be present in a normal admixture gradation. General soils can be 0% to 60% by weight of the total gravel admixture.

In order for the gravel admixture to function as an erosion barrier, there must be a sufficient quantity of gravel in the admixture layer so the admixture layer can protect the soil layers below the admixture layer. The thickness of the gravel portion required to provide erosion protection for the admixture layer is approximately 3 times the computed $D_{50\text{-}min}$. This ratio of the rock layer thickness to $D_{50\text{-}min}$ is greater than commonly used for larger riprap, because of the smaller size material and the reduced precision of individual particle placement. Ratios of 3 to 4 are commonly recommended for finer rock sizes. If the percentage of gravel in the admixture is 80% by weight, the finer material would have a volume nearly equal to the void space between the stable gravel particles, and there would be no need for consideration of additional layer thickness. However, the percentage of gravel in the admixture will be between 5% and 50%, so that a major portion of the required admixture thickness is due the material smaller than gravel. Additional layer thickness is required because the particles smaller than the gravel will be removed by channelized erosive flows. At 45% gravel the total admixture thickness will need to be approximately 5 times the computed $D_{50\text{-}min}$, and at 21% gravel the total admixture thickness will need to be approximately 10 times the computed $D_{50\text{-}min}$.

When a single proposed material gradation is evaluated as a gravel admixture layer, the gradation sizes are compared with the computed $D_{50\text{-}min}$ and $D_{15\text{-}min}$ to determine the *% Gravel*. Then the percentages of the finer soil and the general soil are determined. These values are compared with the allowable percentages for each material classification. Finally the thickness of the total admixture layer is established.

GRAVEL ADMIXTURE SELECTION FOR A GRADATION RANGE

The procedure for the gravel admixture can be used to test for a single specified gradation and determine the applicable layer thickness appropriate to that gradation. It does not directly give the appropriate thickness when a gradation range is specified for a given location. When a gradation range is identified, the material that could be supplied may fall anywhere within the gradation band. Checking the computed thickness for only the minimum and maximum gradations does not provide a thorough examination of the possible gradations. A series of nine possible gradation scenarios within the specified gradation range is examined to determine the critical admixture layer thickness, Y_{Total}, applicable to a single slope and length condition. While each of the gradation scenarios will be within the specified gradation range, computations commonly show that the maximum layer thickness is obtained when using a gradation other than the maximum or minimum gradation. A single thickness and slope is used to compute the Y_{Total} for a specified gradation, but it is also possible to examine a range of slopes and lengths from 3% to 10% that can utilize the same gradation and Y_{Total}.

APPLICATION OF DESIGN PARAMETERS

A gravel admixture was applied to a typical municipal landfill site in a semi-arid climate. A multiple page spreadsheet was used to perform the computation. A section of a top cover with an area of 0.173 ha (0.428 ac) and a uniform slope of 0.05 m/m is considered. A summary of the design parameters are given below:

Design storm for erosion stability = 100-year frequency (1% per year)
Top slope = 0.05 m/m (5%)
Overland flow slope length = 83 m (273 ft)
Peak flow = 0.071 m^3/s (2.5 cfs)
Unit flow rate = 0.042 m^2/s (0.454 ft^2/s)
Maximum channel velocity = 1.006 m/s (3.30 ft/s)
Hydraulic depth of channel flow = 42 mm (0.138 ft)
Froude number = 1.57
Computed D_{50} of gravel portion = 28 mm (1.11 in.), use 32 mm (1.25 in.)
Required thickness of armor layer = 57 mm (2.25 in.)
Computed thickness of gravel/soil admixture layer, Y_{Total} = 0.254 m (10 in.)

The design admixture gradation for the 0.173 ha area at a slope of 0.05 m/m is shown on Figure 1. The design admixture gradation from Figure 1 with a layer thickness, Y_{Total}, of 0.254 m (10 in) and slope of 0.05 m/m (5%) can also be applied to a spreadsheet analysis for slopes from 0.03 to 0.10 m/m (3 to 10%). Slopes flatter than 0.05 m/m will allow larger runoff areas and longer overland flow slope lengths, and slopes steeper than 0.05 m/m will require smaller runoff areas and shorter overland flow slope lengths.

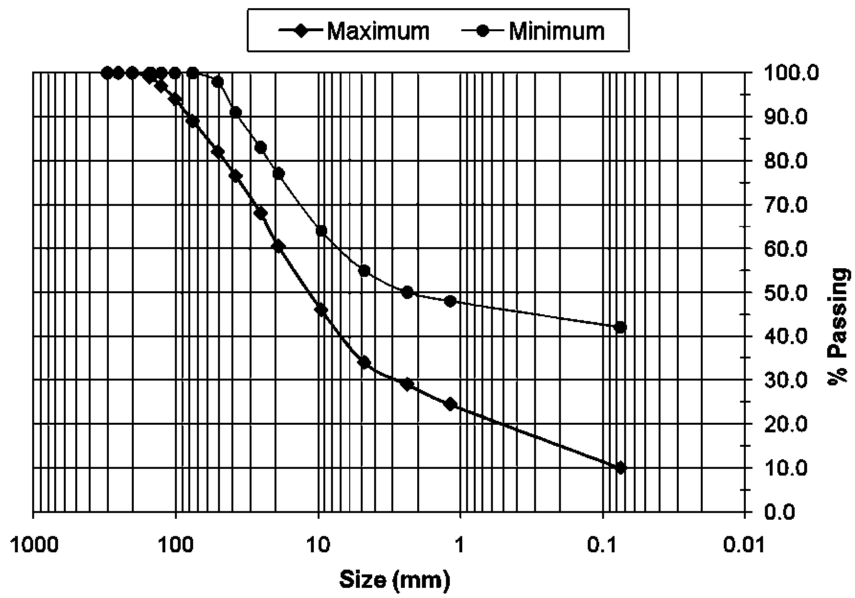


Figure 1. Admixture Gradation for 0.173 ha @ 5.0%

Table 1 shows values for the runoff areas and overland flow lengths that can be applied to the Figure 1 gradation with a 0.254 m (10 in) layer thickness. Moderate increases in the allowable runoff areas and overland flow lengths can also be obtained by increasing the layer thickness to 0.305 m (12 in) for the same gradation range. Table 1 also shows the areas and overland flow length when the thickness is increased.

Table 1. Gravel Admixture Runoff Areas and Overland Flow Lengths

Layer thickness (m)	Max. Area at 3% slope (ha)	Max. Area at 4% slope (ha)	Max. Area at 5% slope (ha)	Max. Area at 6% slope (ha)	Max. Area at 7% slope (ha)	Max. Area at 8% slope (ha)	Max. Area at 9% slope (ha)	Max. Area at 10% slope (ha)
0.254	0.372	0.244	0.173	0.130	0.103	0.084	0.070	0.060
0.305	0.590	0.379	0.270	0.203	0.161	0.132	0.109	0.093
Layer thickness (m)	Max. Length at 3% slope (m)	Max. Length at 4% slope (m)	Max. Length at 5% slope (m)	Max. Length at 6% slope (m)	Max. Length at 7% slope (m)	Max. Length at 8% slope (m)	Max. Length at 9% slope (m)	Max. Length at 10% slope (m)
0.254	122	99	83	72	64	58	53	49
0.305	154	123	104	90	80	73	66	61

A similar gravel admixture design was applied to a demonstration landfill cover constructed in northwestern New Mexico (Anderson and Stormont, 2005). The procedure described here is being applied to a landfill cover soon to be constructed in southern Nevada. The Nevada project will provide the first large scale application of the procedure.

CONCLUSIONS

Measures to control erosion are a significant part of the safe function of landfills. While measures such as revegetation and application of organic mulches may reduce erosion in some climates, mechanical stabilization by a gravel veneer or a gravel admixture layer will likely be required to prevent water erosion in the arid and semi-arid Southwest. The design method for gravel admixtures presented here may provide erosion protection that does not reduce the evaporation rate, or create a habitat for deep-rooted plants.

REFERENCES

Abt, S. R. and Johnson, T. L. (1991). “Riprap Design for Overtopping Flow.” *Journal of Hydraulic Engineering*, 117 (8), pp 959-972.

Anderson, C. E., and Stormont, J. C. (2005). "Gravel Advixtures for Erosion Protection in Semi-Arid Climates." *Erosion of Soils and Scour of Foundations, Proceedings of Sessions of the Geo-Frontiers 2005 Congress*, Austin, Texas.

Anderson, G. K, et al, (1970). Tentative Design Procedure for Riprap-Lined Channels, Highway Research Board, NCHRP Report Number 108.

Finley, J. B., Harvey, M. D., and Watson, C. C. (1985). "Experimental Study: Erosion of Overburden Cap Material Protected by Rock Mulch." *Seventh Symposium on Management of Uranium Mill Tailings, Low-Level Waste and Hazardous Waste*, Fort Collins, Colorado, 273-282.

Kemper, W. D., Nicks, A. D., and Corey, A. T. (1994). "Accumulation of Water in Soils under Gravel and Sand Mulches." *Soil Science Society of America Journal*, 58, 56-63.

Simons, D. B., Li, R. M., et al. (1980). *Watershed and Stream Mechanics*, prepared for the US Department of Agriculture, Soil Conservation Service, Washington, D.C.

Simons, Li and Associates (1982). *Engineering Analysis of Fluvial Systems*, Fort Collins, CO.

Waugh, W. J., and Petersen, K. L. (1994). "Paleoclimatic Data Application: Long-term Performance of Uranium Mill Tailings Repositories." *Climate Change in the Four Corners and Adjacent Regions: Implications for Environmental Restoration and Land-Use Planning, Proceedings of the Workshop*, Mesa State College, Grand Junction, Colorado, 163-185.

Wischmeier, W. H., and Smith, D. D. (1978). "Predicting Rainfall Erosion Losses, A Guide to Conservation Planning." *Agriculture Handbook Number 537*, United States Department of Agriculture, Science and Education Administration, Washington, D.C.

Reference: Pages 1064 to 1073; *Geotechnical Special Publication No. 210, Scour and Erosion, Proceedings of the Fifth International Conference on Scour and Erosion (ISE-5)*; November 7-10, 2010; San Francisco, CA, USA; S.E. Burns, S.K. Bhatia, C.M.C. Avila and B.E. Hunt editors; published by the American Society of Civil Engineers, Reston, VA; 2011; ISBN 978-0-7844-1147-6.

Erosion Protection at Landfill Slopes Greater than 10%

Clifford Anderson[1], M. ASCE, PE, PhD, D.WRE and Steve Wall[2]

[1]Department of Engineering, Central Connecticut State University, 1615 Stanley Street, New Britain, CT 06050-4010, USA, email: cliff@ahymo.com

[2]Office of Pollution Prevention and Solid Waste (WST-7), US EPA Region 9, 75 Hawthorne St., San Francisco, CA 94105, USA, email: Wall.Steve@epamail.epa.gov

ABSTRACT

In arid climates the steep side slopes of a landfill can be sources of severe erosion. The amount of vegetation that can be sustained commonly does not provide significant erosion protection, and alternative erosion protection measures are required. The commonly used side slope terrace drains can be difficult to construct and maintain. A method is presented to compute the gradation and thickness of a rock surface erosion protection layer that will allow for longer slope lengths than has been commonly applied. The procedure considers peak flow, slope and the formation of surface channelization. Criteria for applying a granular filter are also considered. As an alternative to separately placed riprap and granular filter layers, a combined mixture could serve the same function as separate layers, and reduce construction costs. A gradation range is considered for a combined mixture, and a series of gradations within the range is examined to determine the critical layer thickness. Examples of a resulting side slope design are presented.

INTRODUCTION

The steep side slopes of a landfill can be sources of erosion if surface runoff is allowed to accumulate on the steep slopes and the side slope surfaces are constructed with erosive materials. In some climates, vegetation can be utilized to reduce runoff velocities and stabilize surface soils. In arid climates the amount of vegetation that can be sustained commonly does not provide significant erosion protection, and alternative erosion protection measures are required. One erosion protection method commonly used limits the slopes to short lengths by the construction of side slope terrace drains, with additional protection provided by the addition of gravel armoring to the slopes. Side slope terrace drains can be difficult to construct and maintain, and their placement on existing slopes may provide additional construction difficulties. The procedures described in this document can be used to guide the design of a rock surface erosion protection layer that will allow for longer slope lengths than has been commonly applied. The longer slope lengths may greatly reduce or eliminate the need for side slope terrace drains.

It is desirable to reduce the amount of surface water that can enter the zone of fill, and this is typically accomplished by construction of a barrier layer above the area of fill. Studies in arid climates have shown that a thick soil layer can provide a superior barrier layer, because of the moisture storage properties of the soil, and high rates of evaporation and plant transpiration. Some studies have indicated that placement of a surface gravel layer will increase surface infiltration and reduce evaporation so that the efficiency of a soil barrier layer is reduced. However, for very steep slopes the runoff percentages will be much higher than for flatter slopes, and the effects of surface gravel on overall evaporation will be minimized. When slopes are at 10% or steeper, and the base soil does not allow for the rapid infiltration of surface water, a gravel layer or "veneer" can provide surface erosion protection without significantly reducing the function of the soil barrier layer.

The size of the gravel and layer thickness is normally based on a constructed watershed condition and a critical design slope. The design of a gravel veneer to protect steep side slopes from erosion requires evaluation of small watershed hydrology and hydraulics, and the design of the conveyances where water is expected to flow. In the case of steep uniformly graded or gradually varying embankment slopes, a fixed flow path or channel may not be constructed on the surface, but channelization will occur because of normal construction variability, settlement, and on-going erosion processes. Site physical conditions and experience at similar existing sloped areas can be used to establish surface flow criteria using geomorphologic equations. The resulting flow rates and velocities based on geomorphology will generally be larger than when only existing or constructed site topography is used.

Construction of a gravel veneer commonly includes a separately placed finer filter soil below the gravel, but construction could be simplified if the filtering material could be placed concurrently with the gravel. The design of a combined gravel-filter erosion layer is described in this document.

Using critical flow depth, velocity and slope criteria, a single gravel veneer gradation and thickness can be designed. When slopes and runoff areas vary widely, an alternative approach is to use preliminary analyses to determine veneer gradations, then to use this information as a guide for selection of material gradations that can be efficiently produced. Each selected gradation can then be evaluated to determine the range of site conditions where the gradation can be safely applied.

PEAK FLOW AND UNIT DISCHARGE

Erosion of landfill side slopes is most problematic during severe precipitation when erosion can remove waste from a landfill and convey it to downstream areas. For a landfill side slope in the arid and semi-arid areas of the southwest United States a 200-year event is a suggested design flow condition, because of the significant environmental damage that can result from side slope erosion. Special site requirements and waste materials may warrant use of more severe event frequencies. For any given watershed, the 200-year frequency event peak flow (Q_{200}) can be determined from a basic hydrologic analysis, such as with the Rational Method or NRCS Curve Number (*CN*) procedure. Peak flow during the storm event is the most important hydrologic property to accurately predict erosion. For a planar surface with an identified length, but a width that can be identified only after erosion has occurred, the recommended watershed width for runoff computations should be 25% of the watershed length. The dominant discharge peak flow (Q_m) can evaluated by considering the statistically weighted average of the peak runoff occurring over a long period, for example 100 years. In the arid southwestern the Q_m can be estimated at 10% of Q_{100}. For any given watershed, the relationship between the 200-year frequency event peak flow (Q_{200}) and the 100-year frequency event peak flow (Q_{100}) can be determined from a basic hydrologic analysis. Therefore, the value of Q_{100}/Q_{200} will have a fixed value for any single watershed. The ratio of Q_m/Q_{200} can be determined from Q_m/Q_{100} and Q_{100}/Q_{200}. For example, if the Q_{100}/Q_{200} is determined to be 0.78, the Q_m can be estimated as 7.8% of Q_{200}.

By following the analysis procedure described in "Design of Erosion Protection at Landfill Areas with Slopes Less than 10%" (Anderson and Wall, 2010, this volume), and substituting the Q_{200} for the Q_{100}, the hydraulic depth equation is:

$$d_h = (43.7)^{-0.6} \left(\frac{Q_m}{Q_{200}}\right)^{-0.6} Q_m^{0.372} \left[0.0488 \left(\frac{D_{50}}{1000}\right)^{0.167}\right]^{0.6} s^{-0.3} M^{0.234} \quad [1]$$

where: d_h is the hydraulic depth (m),
Q_{200} is the peak flow at 200-year frequency (m^3/s),
Q_m is the dominant discharge (m^3/s),
D_{50} is the median size of the rock riprap (mm).
M is the percentage of silt and clay in the channel perimeter
and s is the slope of the channel profile (m/m).

Equation [1] describes the flow width based on the geomorphologic equation of Simons, Li and Associates (1982, and Simons and Li, 1980). Except for the D_{50}, all of the values in this equation can be estimated from physical watershed properties. This equation and Manning's equation can also be used to compute the 200-year event unit discharge, Q_{200}/b, and the width-to-depth ratio, b/d_h. While the dominant discharge, Q_m, is used in equation [1], the computed hydraulic depth, d_h, represents the depth from a 200-year frequency event.

A second geomorphologic parameter is the width-to-depth ratio of the flowing water. For arid and semi-arid conditions a maximum width-to-depth ratio of 40 is recommended. If the width-to-depth ratio, b/d_h, exceeds 40, the b and the d_h must be re-computed to maintain a width-to-depth ratio of 40. The width-to-depth relation can be used to obtain an alternate equation for the hydraulic depth as:

$$d_h = [(Q_{200}\ n)/F]^{0.375}\ s^{-0.1875} \quad [2]$$

where: F is the width-to-depth ratio. (Use a value of 40)
and n is the Manning's roughness coefficient.

Equation [2] describes the flow width and depth based on a defined width-to-depth ratio. Equation [2] should be used whenever the b/d_h computed from equation [1] exceeds 40. Using Manning's equation and equation [1] or [2], the flow velocity, V_{100}, the Froude number, F_r, the width of flow, b, and the unit discharge, q_f, can be computed.

RIPRAP ROCK SIZE

With the flow properties established, the S. R. Abt and T. L. Johnson equation (1991) can be used to solve for the median rock size of the gravel veneer. The basic Abt and Johnson equation provides a prediction of the flow conditions when failure is expected to occur, but for constructed applications, failure at the design flow is not tolerable. "Riprap design should be directed toward preventing stone movement and to insure the riprap layer does not fail" (Abt and Johnson, 1991, page 962). Abt and Johnson state that the values from the basic equation "should be adjusted to prevent stone movement" (Abt and Johnson, 1991, page 967). In addition, actual construction is expected to be somewhat more variable than the hand placement of rock in a controlled laboratory experiment, and minor construction variability could cause failure prior to the conditions identified in the Abt and Johnson field laboratory testing. Abt and Johnson recommend that factor of safety of 1.2 be applied to the rock size equation (page 967).

The Abt and Johnson equation uses the unit discharge, and profile slope to compute the median rock size when failure is expected to occur. The unit discharge is computed using the smallest *b* derived using Manning's equation and equation [1] or [2] so that the computed unit discharge is the maximum value computed from the two equations. The equation for unit discharge is:

$$q_f = Q_{200}/b \qquad [3]$$

where: q_f is the unit discharge or unit flow rate (m^2/s).

The Abt and Johnson equation with the addition of the recommended factor of safety and converted to metric form is:

$$D_{50} = (1.2 \times 502.9)\, s^{0.43}\, q_f^{0.56} \qquad [4]$$

where: D_{50} is the median rock size of the gravel veneer (mm).

The physical testing by Abt and Johnson did not use slopes steeper than 20% (0.20 m/m) and the extension of the procedure to slopes steeper than 33% (0.33 m/m) is not recommended. Abt and Johnson's paper suggested that the gravel layer thickness should be 1.5 to 3.0 times the D_{50}. However, only two of their 26 tests had a layer thickness less than 2.0 times the D_{50}. All of their tests were for separately placed riprap and granular filter layers.

CRITERIA FOR GRAVER VENEER RIPRAP AND FILTER

The D_{50} computed from equation [4] can be used to determine the rock gradation for the gravel veneer and the total thickness of the veneer layer. The following procedure is recommended:

- specify a construction minimum D_{50} ($D_{50\text{-}min}$) based on the computed value from equation [4] rounded to the nearest 6.4 mm (0.25 inch).

- specify a design maximum D_{50} ($D_{50\text{-}max}$) at 140% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify a minimum D_{100} ($D_{100\text{-}min}$) at 150% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{100} ($D_{100\text{-}max}$) at 200% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch). The constructed veneer can have a larger value with an appropriate adjustment in the layer thickness.
- specify a minimum D_{15} ($D_{15\text{-}min}$) at 45% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{15} ($D_{15\text{-}max}$) at 80% of the $D_{50\text{-}min}$, rounded to the nearest 6.4 mm (0.25 inch).
- specify the coefficient of uniformity ($C_u = D_{60} / D_{10}$) with an allowable range between 1.75 and 3.0.
- specify the minimum rock layer thickness (Y_{min}) at the 2.0 times the $D_{50\text{-}min}$, or 1.0 times the $D_{100\text{-}max}$, whichever is larger.

The Abt and Johnson physical testing used rock with an average specific gravity of 2.66. In order to use equation [4] without adjustment, the rock in the gravel veneer should have an average specific gravity of 2.65 or larger. This is equivalent to a particle unit weight of 2650 kg/m^3 (165 lbs/ft^3). If any rock with a smaller average specific gravity is proposed for use, the size of the D_{15}, D_{50}, D_{100}, and Y_{min} would need to be adjusted based on the ratio of the buoyant weight of the rock.

The gravel veneer in the Abt and Johnson testing used a granular filter immediately below the rock layer. Filter material is placed below the rock layer to prevent loss of material below the layer which would cause failure of the erosion layer. The size of the granular bedding must be based on size of the gravel in the erosion layer. Some guidelines on granular filter design can be found in the US Federal Highway Administration, Hydraulic Engineering Circular No. 11 (1989, FHWA-IP-89-016). The following procedure is recommended:

- specify a minimum *Filter* D_{85} (*Filter* $D_{85\text{-}min}$) at 20% of the maximum veneer D_{15} ($D_{15\text{-}max}$), rounded to the nearest 0.25 mm (0.01 inch).
- specify a minimum *Filter* D_{50} (*Filter* $D_{50\text{-}min}$) at 4% of the maximum veneer D_{50} ($D_{50\text{-}max}$), rounded to the nearest 0.25 mm (0.01 inch).
- specify a design minimum *Filter* D_{60} (*Filter* $D_{60\text{-}min}$) at 140% of the minimum *Filter* D_{50} (*Filter* $D_{50\text{-}min}$), rounded to the nearest 0.25 mm (0.01 inch).
- specify a design minimum *Filter* D_{10} (*Filter* $D_{10\text{-}min}$) at the minimum *Filter* D_{60} (*Filter* $D_{60\text{-}min}$) divided by 3.5, rounded to the nearest 0.25 mm (0.01 inch).
- specify the Filter coefficient of uniformity (*Filter* C_u = *Filter* D_{60} / *Filter* D_{10}) with an allowable range between 2.0 and 3.5.
- specify the minimum Filter layer thickness (*Filter* Y_{min}) at 0.152 m (6.0 inches).

For the range of gravel veneer sizes that are likely to be required for steep landfill slopes, a typical roadway aggregate base will typically contain a higher percentage of finer grained soils than is recommended to meet granular filter criteria. Table 1 provides two granular filter gradations that might be considered with steep sloped rock layers. The Type A Granular Soil Filter in Table 1 can generally be used when the veneer $D_{50\text{-}min}$ is 100 mm (4.0 inches) or less. The Type B Granular Soil Filter can generally be used when the veneer $D_{50\text{-}min}$ is between 100 mm (4.0 inches) and 180 mm (7.0 inches). A somewhat finer filter could be specified for cases where the $D_{50\text{-}min}$ is smaller than 65 mm (2.5 inches). For each gravel veneer size, the *Filter* $D_{85\text{-}min}$, *Filter* $D_{50\text{-}min}$, and *Filter* $D_{10\text{-}min}$ should be examined to verify that the appropriate Granular Filter Soil (Type A or B) is used.

Table 1. Suggested Granular Filter Gradations

Granular Filter Soil - Type A		Granular Filter Soil - Type B	
Passing	% by weight	Passing	% by weight
75 mm (3 inch)	100%	100 mm (4 inch)	100%
20 mm (3/4 inch)	30 to 90%	25 mm (1 inch)	30 to 80%
10 mm (3/8 inch)	10 to 70%	10 mm (3/8 inch)	5 to 40%
#4 (0.475 mm)	0 to 20%	#4 (0.475 mm)	0 to 20%
#200	0 to 3%	#200	0 to 3%

A SINGLE RIPRAP-FILTER LAYER

As an alternative to separately placed riprap and granular filter layers, a combined material layer could serve the same function as the separate layers, and reduce construction costs. With a riprap-filter mixture the resulting material properties need to be examined to determine if the erosion protection and the filtering criteria can be met. With the riprap-filter mix, it is possible to perform some material selection and processing to produce different classes of mix, but more refined material selection may not be feasible.

Rather than specify detailed rock and filter gradations applicable to a single design flow and slope, a preliminary design to determine rock and filter gradations can be used in selecting a riprap-filter mixture that can be efficiently produced. Even with material from a single source area, it is expected that there will be variability of test results. The arithmetic mean and standard deviation of the test data are important measurements to obtain a specified gradation range. It may be desirable to specify a wider range of particle sizes than would be indicated by statistical sampling of a single source in order to allow greater flexibility in material source selection and processing. However, a larger range of values will change the layer erosion protection capability and may reduce the design efficiency. There are limits to the range of allowable gradations. For example, if there is not a sufficient quantity of particles that resist the erosive forces, no additional thickness can compensate for this deficiency.

With a specified riprap-filter mix the gradation of the portion of the mix that can be considered to as riprap must be considered. Particles sizes at “25% of the D_{50}" can carry only 8.4% of the unit discharge of particles at “100% of the D_{50}". Based on examination of riprap guide specifications from several sources, particle sizes in the riprap-filter mix that are smaller than 25% of the computed D_{50}, should not be included in the riprap portion of the mix. The US Dept. of Transportation, Federal Highway Administration, *Design of Riprap Revetment* (Hydraulic Engineering Circular, FHWA-IP-89-016, 1989, p.36) recommends D15 at 40% to 60% of the D_{50}. The percentage of riprap size material in a proposed gradation can be determined from the percentage of material passing the computed “25% of the D_{50}", where:

$$\%Riprap = 100\% - \%\text{ passing "25\% of } D_{50}\text{"} \qquad [5]$$

Using a similar procedure, the percentage of effective filtering material can be determined. For the range of gravel sizes expected, any particle sizes that pass a #10 sieve (2.0 mm) should not be considered as contributing to riprap filtering. Therefore the percentage of filter material in a gradation can be computed as:

$$\%\,Filter = \%\text{ passing “25\% of } D_{50}\text{"} - \%\text{ passing \#10 sieve (2.0 mm)} \qquad [6]$$

With the % *Riprap* and % *Filter* established, it is also possible to use the total grain size distribution to obtain an equivalent riprap grain size distribution for the portion of the particle sizes that can be considered as riprap. The individual sieve size percent passing values for the riprap portion are computed as:

$$\%\,passing\ riprap\ portion = 100\%\left(1 - {(100\% - \%\text{passing})}\big/{\%\text{riprap}}\right) \qquad [7]$$

Using the grain size values for the riprap portion, the $D_{15\ riprap}$, $D_{50\ riprap}$, $D_{85\ riprap}$ and $D_{98\ riprap}$ of the riprap can be computed. The basic riprap layer thickness is computed as:

$$T_{Riprap\text{-}1} = 1.6 \times D_{50\ Riprap} \qquad \text{or} \qquad [8]$$

$$T_{Riprap\text{-}1} = (0.6 \times D_{90\ Riprap}) + (0.9 \times D_{85\ Riprap}) \qquad [9]$$

whichever is smaller, but not less than:

$$\mathrm{T}_{\mathrm{Riprap\text{-}1}} = 2 \times \text{computed } \mathrm{D}_{50} \qquad [10]$$

When the $D_{15\ riprap}$ is smaller than 40% of the computed D_{50}, there is more small size material than is recommended for a normal riprap gradation and the riprap layer thicknesses should be adjusted for the excess of smaller material by the following equation:

$$T_{Riprap\text{-}2} = \left[1 - \left(\frac{0.15\left(\ln\left(D_{15Riprap}\right) - \ln(25\%\text{ comp } D_{50})\right)}{\ln\,(40\%\text{ comp } D_{50}) - \ln(25\%\text{ comp } D_{50})}\right)\right]\left(\frac{T_{Riprap\text{-}1}}{0.85}\right) \qquad [11]$$

When the sample $D_{50\ riprap}$ is smaller than the computed D_{50}, the average size of the riprap is too small and the riprap layer thickness is adjusted by the following equation:

$$T_{Riprap\text{-}3} = \left[1 - \left(\frac{0.50\left(\ln\left(D_{50Riprap}\right) - \ln(25\%\text{ comp } D_{50})\right)}{\ln\,(40\%\text{ comp } D_{50}) - \ln(25\%\text{ comp } D_{50})}\right)\right]\left(\frac{T_{Riprap\text{-}1}}{0.50}\right) \qquad [12]$$

The riprap layer thickness then is the largest value, or:

$$T_{Riprap} = \text{Maximum}\left(T_{Riprap\text{-}1}, T_{Riprap\text{-}2}, T_{Riprap\text{-}3}\right) \qquad [13]$$

The minimum percentage of filter in the gravel-soil mix is determined from the following equation derived from typical riprap filter designs:

$$Min\,\%\,Filter = \%Riprap \times (15\%\text{ of } D_{50})/4.0 \qquad [14]$$

but not less than 0.10 × *% Riprap* or more than 0.25 × *% Riprap*. The computed *% Filter* material is compared with this sample value, and if the *Min % Filter* is greater than the *% Filter* provided, the total layer thickness is adjusted.

If the percentage of the material finer than the Riprap size in the sample gradation does not exceed 25%, and the *Minimum % Filter* does not exceed the *% Filter* provided by the gradation, the computed T_{Riprap} will also be the computed layer thickness. When these conditions are not met, the total layer thickness must be adjusted to account for filter bulking or *% Filter* deficiency. The following equation is used:

$$T_{Layer} = \left[Max\left(\frac{75\%}{\%Riprap}, 1\right)\right] \times \left[Max\left(\frac{Min\,\%Filter}{\%Filter}, 1\right)\right] \times T_{Riprap} \qquad [15]$$

with T_{Layer} never less than T_{Riprap}.

GRAVEL RIPRAP-FILTER SELECTION FOR A GRADATION RANGE

The procedure for the riprap-filter mix can be used to test a single specified gradation and determine the applicable layer thickness appropriate to that gradation. It does not directly give the appropriate thickness when a gradation range is specified for a given location. When a gradation range is identified, the material that could be supplied may fall anywhere within the gradation band. Checking the computed thickness for only the minimum and maximum gradations does not provide a thorough examination of the possible gradations. A series of nine gradation scenarios within the gradation range is examined to determine the critical admixture layer thickness, T_{Layer}, applicable to a single slope and length condition. With a single thickness and slope used to compute the T_{Layer}, for a specified gradation, it is also possible to examine a range of slopes and lengths from 10% to 30% that can utilize the same gradation and T_{Layer}.

APPLICATION OF DESIGN PARAMETERS

A riprap-filter mix was applied to a typical landfill side slope in an arid climate. A multiple page spreadsheet was used to perform the computation. A section of the side slope with an area of 0.468 ha (1.157 ac) and a uniform slope of 0.20 m/m was considered. A summary of the design parameters are given below:

Design storm for erosion stability = 200-year frequency (0.5% per year)
Top slope = 0.20 m/m (20%)
Overland flow slope length = 137 m (449 ft)
Peak flow = 0.319 m^3/s (11.27 cfs)
Unit flow rate = 0.130 m^2/s (1.396 ft^2/s)
Maximum channel velocity = 2.11 m/s (6.92 ft/s)
Hydraulic depth of channel flow = 62 mm (0.202 ft)
Computed D_{50} of riprap portion = 96 mm (3.79 in.), use 95 mm (3.75 in.)
Required thickness of riprap only = 0.203 m (8.00 in.)
Computed thickness of riprap-filter layer, T_{Layer} = 0.254 m (10 in.)

The design admixture gradation for the 0.468 ha area at a slope of 0.20 m/m is shown on Figure 1.

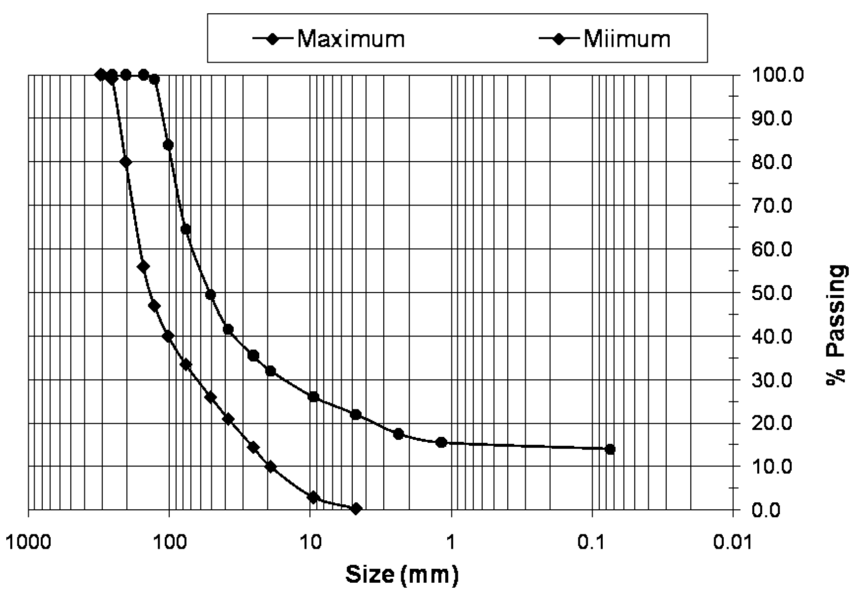


Figure 1. Combined Riprap-Filter Gradation

The design admixture gradation from Figure 1 with a layer thickness, T_{Layer}, of 0.254 m (10 in) and slope of 0.20 m/m (20%) can also be applied to a spreadsheet analysis for slopes from 0.10 to 0.30 m/m (10 to 30%). Slopes flatter than 0.20 m/m will allow larger runoff areas and longer overland flow slope lengths, and slopes steeper than 0.20 m/m will require smaller runoff areas and shorter overland flow slope lengths. Table 2 shows values for the runoff areas and overland flow lengths that can be applied to the Figure 1 gradation with a 0.254 m (10 in) layer thickness.

Table 2. Riprap-Filter Mix Runoff Areas and Overland Flow Lengths

Layer thickness (m)	Max. Area at ≤12% slope (ha)	Max. Area at ≤14% slope (ha)	Max. Area at ≤16% slope (ha)	Max. Area at ≤18% slope (ha)	Max. Area at ≤20% slope (ha)	Max. Area at ≤22% slope (ha)	Max. Area at ≤26% slope (ha)	Max. Area at ≤30% slope (ha)
0.254	1.024	0.808	0.660	0.551	0.468	0.406	0.313	0.251
Layer thickness (m)	Max. Length at ≤12% slope (m)	Max. Length at ≤14% slope (m)	Max. Length at ≤16% slope (m)	Max. Length at ≤18% slope (m)	Max. Length at ≤20% slope (m)	Max. Length at ≤22% slope (m)	Max. Length at ≤26% slope (m)	Max. Length at ≤30% slope (m)
0.254	202	180	162	148	137	127	112	100

CONCLUSIONS

Measures to control erosion at the steep side slopes of a landfill are critical for safe function. Mechanical stabilization of steep slopes by a combined riprap-filter layer can be used to prevent water erosion. Standard rainfall-runoff procedures can be combined with geomorphologic equations to compute channelized flow. Procedures commonly applied to determine riprap size and filter gradation can then modified to establish requirements for a single riprap-filter layer. The resulting riprap-filter gradation can then be evaluated for a range of slope and watershed conditions to determine applicable layer thicknesses. The design method presented here was prepared to guide the construction of erosion protection for steeply sloped areas on a landfill in the arid and semi-arid Southwest. However, the method implements design concepts that are commonly applied at steep slopes, and the design method could be could be readily adapted to any slopes were rock veneers are warranted.

REFERENCES

Abt, S. R. and Johnson, T. L. (1991). "Riprap Design for Overtopping Flow." *Journal of Hydraulic Engineering*, 117 (8), pp 959-972.

Simons, D. B., Li, R. M., et al. (1980). *Watershed and Stream Mechanics*, prepared for the US Department of Agriculture, Soil Conservation Service, Washington, D.C.

Simons, Li and Associates (1982). *Engineering Analysis of Fluvial Systems*, Fort Collins, CO.

US Federal Highway Administration (1989). *Design of Riprap Revetment*, Hydraulic Engineering Circular No. 11, FHWA-IP-89-016, Washington, D. C.